An Introduction to Charged Particle Tracking

Mike Hildreth
University of Notre Dame

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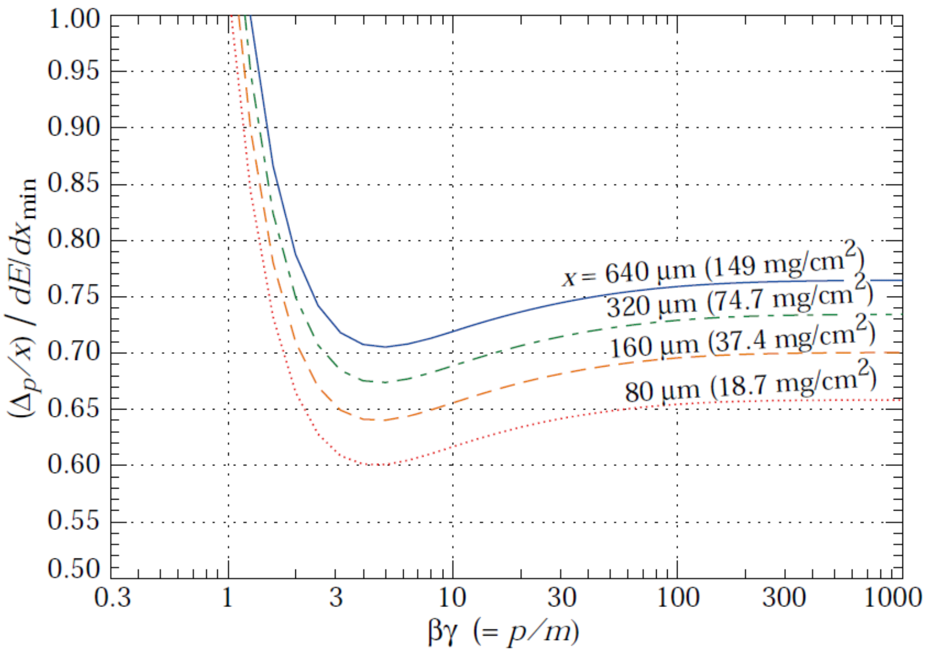
Points of clarification

- Most probable energy loss Δ_p:

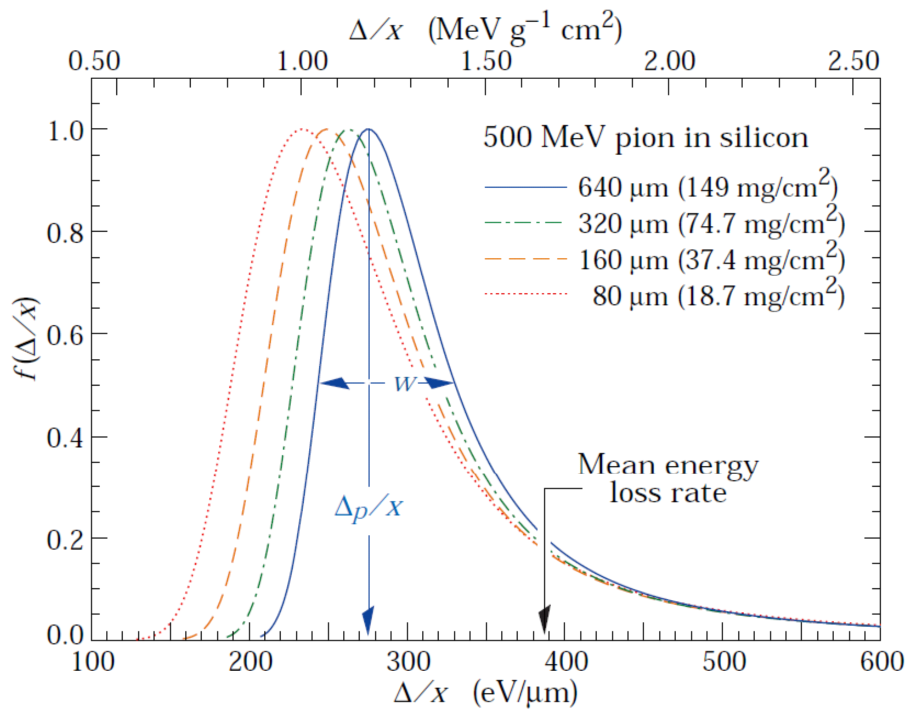
$$\Delta_p = \xi \left[\ln \frac{2mc^2\beta^2\gamma^2}{I} + \ln \frac{\xi}{I} + j - \beta^2 - \delta(\beta\gamma) \right]$$

where $\xi = (K/2)\,\langle Z/A \rangle\,(x/\beta^2)$ MeV for a detector of thickness x.

- So, Δ_p is a function of thickness, whereas dE/dx is not: $\Delta_p/x \propto$ a + b ln$x$



Δ_p/x compared with minimum dE/dx



shape of Δ_p/x

Points of clarification

- Momentum error due to multiple scattering
  - this formula is, in fact, correct:

$$\left.\frac{\sigma(p_T)}{p_T}\right|^{ms} = \frac{28\ MeV}{0.3 \cdot BL}\sqrt{x/X_0}\,\frac{p_T}{\beta c p}$$

  - so, at high momentum, the factor

$$\frac{p_T}{\beta c p} \rightarrow \text{const.}$$

  - Another way to see this: sagitta $s \propto \frac{0.3BL^2}{8p_T}$, MS angle $\theta_0 \propto \frac{1}{\beta cp}$
    - this implies $\sigma^{MS}(s) \propto \frac{1}{\beta cp}$, so $\frac{\sigma(s)}{s} \propto \frac{p_T}{\beta cp} \propto \frac{1}{\beta}$
  - FYI: Old PDG Reviews (e.g. 1996) had whole sections on tracking in magnetic fields. Deleted in more modern versions

Overview:

- *Outline for these lectures*
  - *Lecture 1:*
    - *Motivation*
    - *Tracking vocabulary*
    - *Detector Techniques*
  - *Lecture 2:*
    - *Algorithmic Techniques for Pattern Recognition, Fitting*
    - *Tracking system designs*
  - *Lecture 3:*
    - *Commissioning/Calibrating a tracking system*
    - *Environmental Challenges*
      - *Radiation damage, occupancy, etc.*
    - *Tracking information used in event triggers*
    - *Tracker upgrades*

Silicon Detectors

Solid State Tracking Detectors

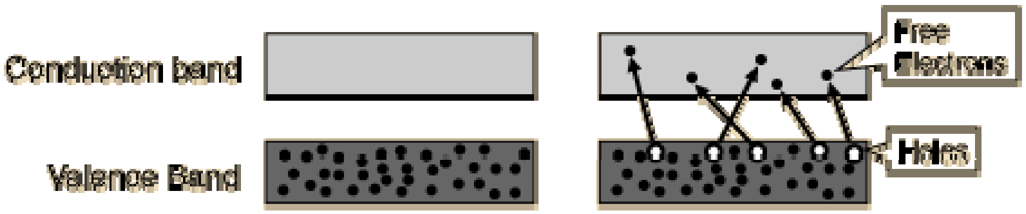
- Why Silicon?
  - crystalline silicon band gap is 1.1 eV (c.f. ~20eV for typical gases)
    - yields 80 electron-hole pairs/μm for minimum-ionizing track
      - (1 e-h pair per 3.6 eV of deposited energy)
    - 99.9% of ejected electrons have less than 1μm path length
      - fine-granularity devices can easily be made

  $\Rightarrow$ detector performance could be as good as emulsion/bubble chamber

  - Integrated Circuit manufacturing techniques make just about anything possible, and at industrial prices
    - no real need to “home-grow” these detectors
    - just buy what you need…

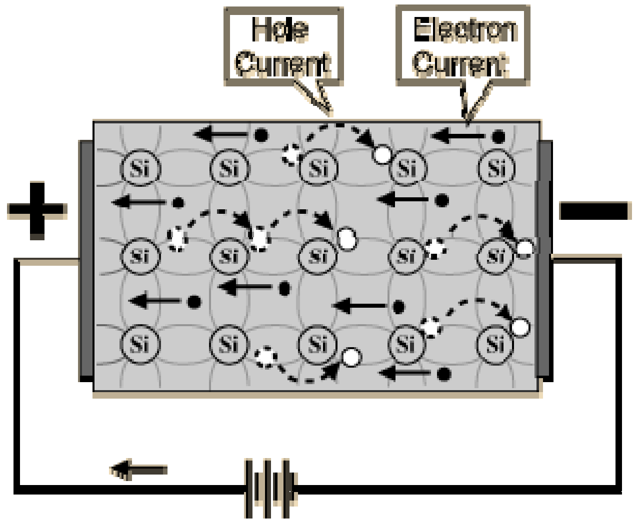
Silicon Basics

- Detection still based on collecting electrons from dE/dx in material
- semiconductor structure:



http://hyperphysics.phy-astr.gsu.edu

electrons excited (thermally or otherwise) into Conduction band become mobile



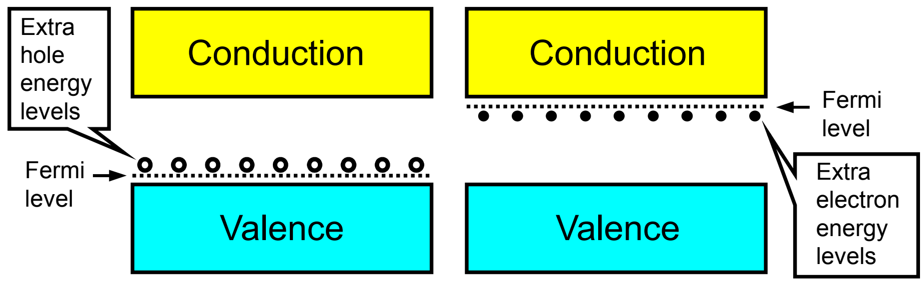
Liberated electrons will drift under the influence of an applied voltage

- the problem: recombination
  - many, many more free charge carriers in a semiconductor than what is liberated through ionization ⇒ electrons re-combine with holes

Silicon Basics: Doping and PN

- The solution(s): 1. modify material structure

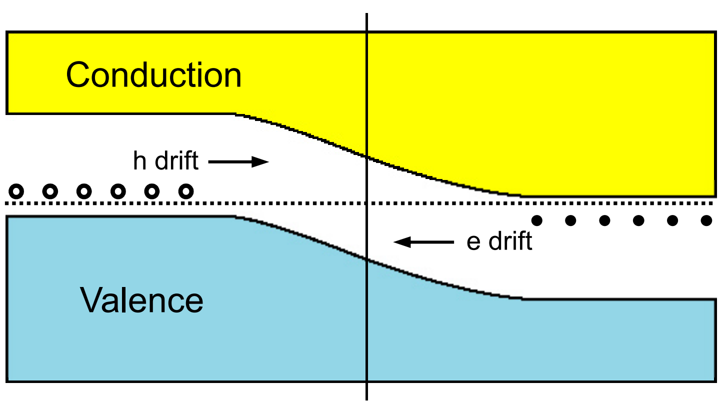
P-type silicon has electron acceptor (hole donor) atoms (B) added to create additional hole states



P Type **N Type**

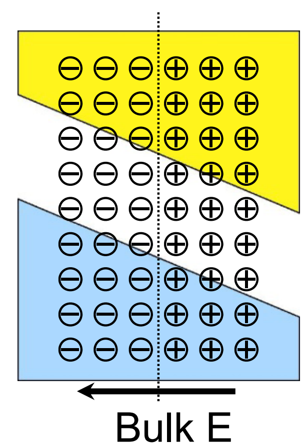
N-type silicon has electron donor atoms (P) added to create additional electron states

2. Modify charge structure: put P and N together (PN Junction)
   – in thermal equilibrium, Fermi levels become equal due to drift of electrons/holes across junction



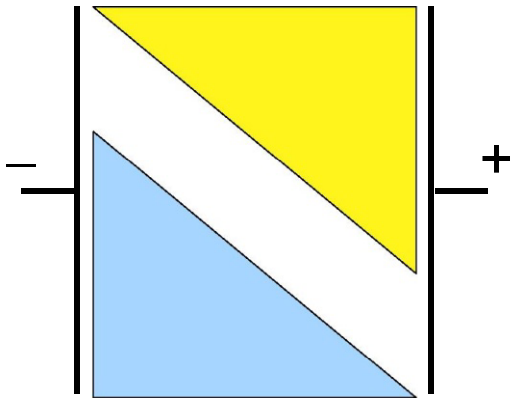
P Type **N Type**

Near junction, electrons bind to hole sites, creating negative ions, leaving positive ions behind. Bulk E-field stops motion of more particles ⇒
Depletion region: no free charge carriers!



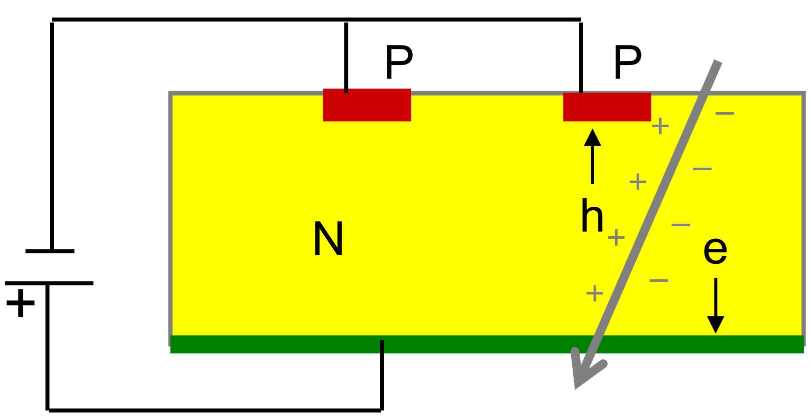
Silicon Basics: PN Junction, Bias

3. Apply a voltage to suppress bulk E field, increase size of depletion layer to encompass entire volume: "Reverse Bias"

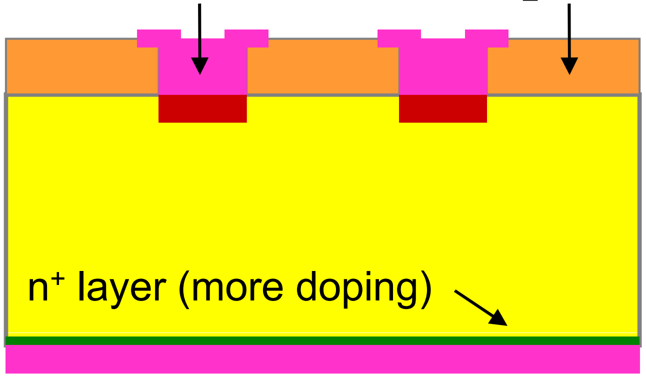


At the depletion voltage, no more free charge carriers exist in the semiconductor; any additional e-h pairs generated can drift to the edges

In reality, use bulk silicon of one type, make "electrodes" out of the other type:

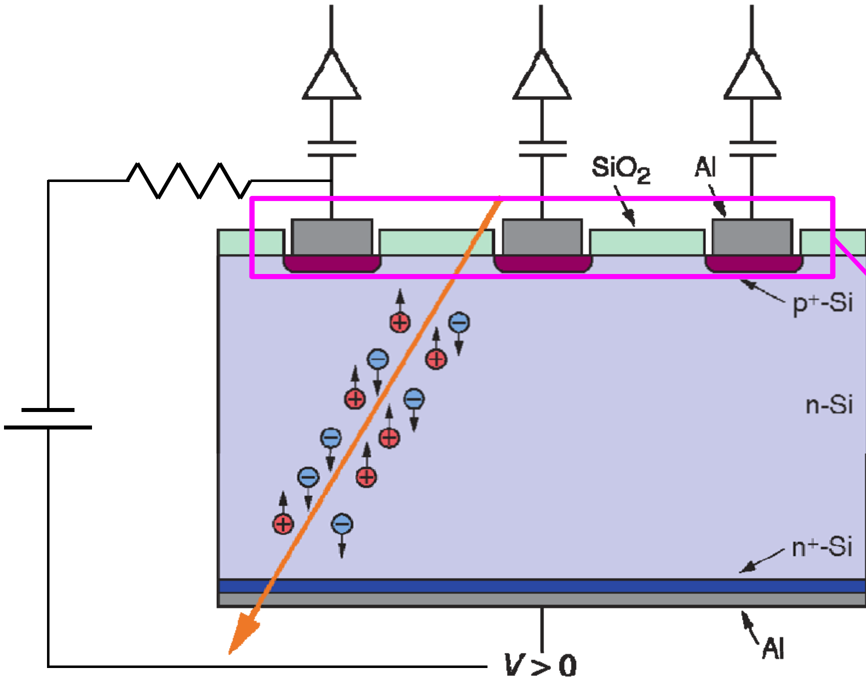


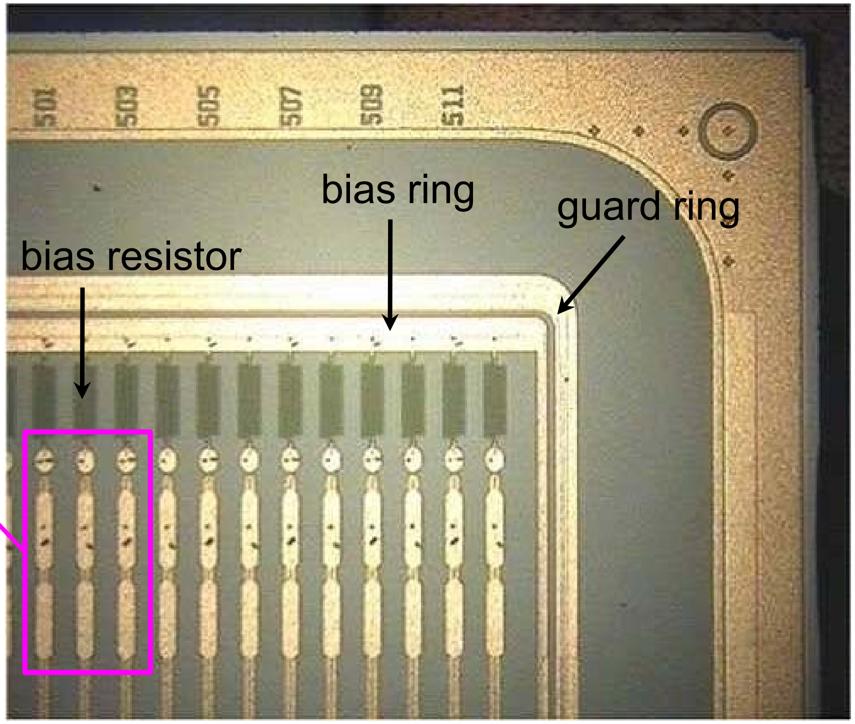
"Real" detectors necessarily more complicated



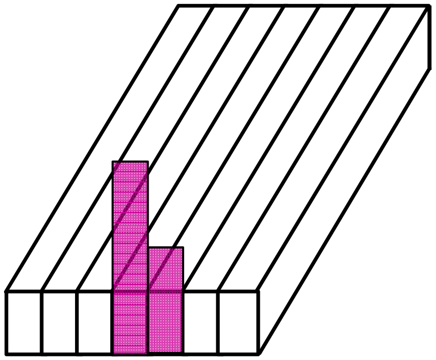
SSTDs: Silicon Microstrips

- The easiest thing to do is put down sensor lines, read out at end





- Charge sharing improves position resolution:

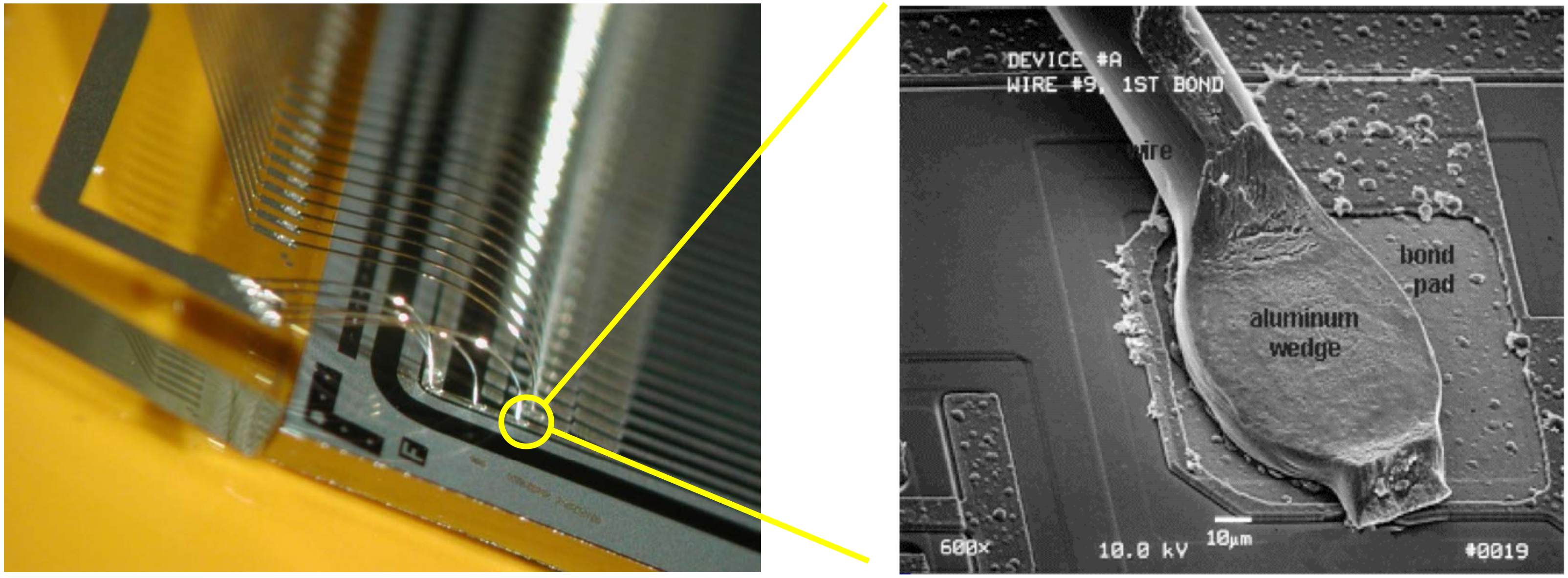


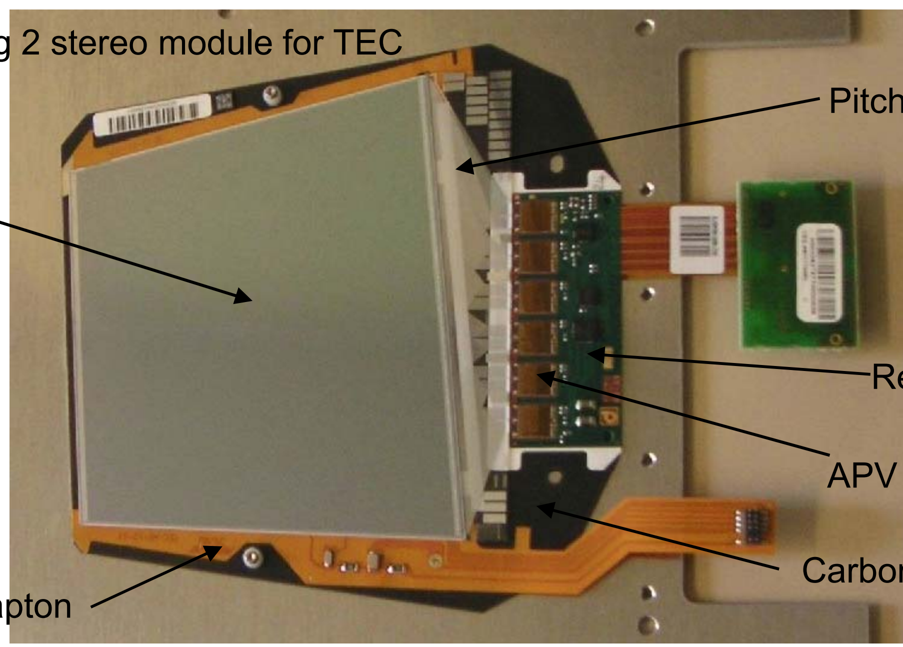
$$\overline{x} = \frac{\sum x_i q_i}{\sum q_i}$$

- Typical pitch width: 50μm – 200μm
  - one strip: width/$\sqrt{12}$
  - two stips: width/4
  - more than two: width/2

SSTDs: Silicon Microstrips

- Exquisitely complicated micro-mechanical construction



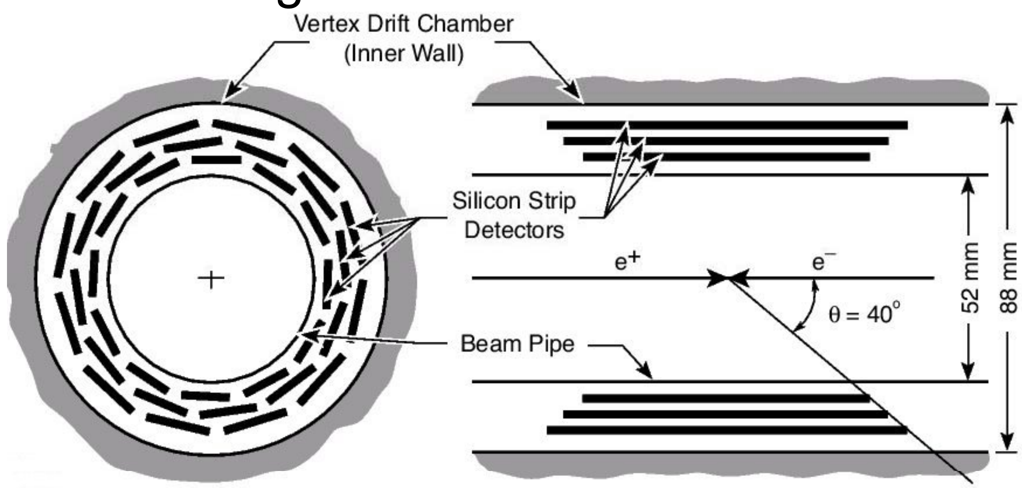


SSTDs: Silicon Microstrips

- inherently 2-D: go to double-sided (or glue sensors at an angle for stereo) for r-z, but still 2-D devices
- “shingle” geometry common
  - full azimuthal coverage

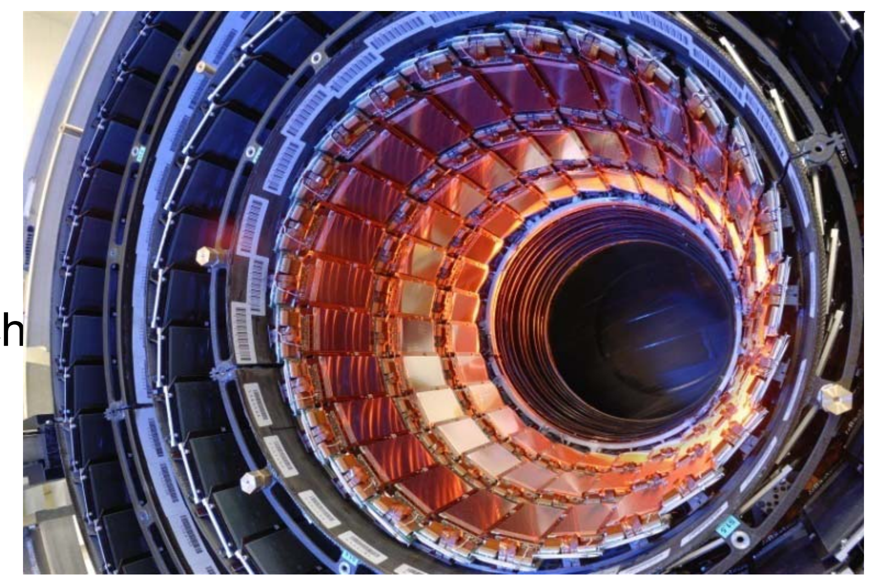
Mark II

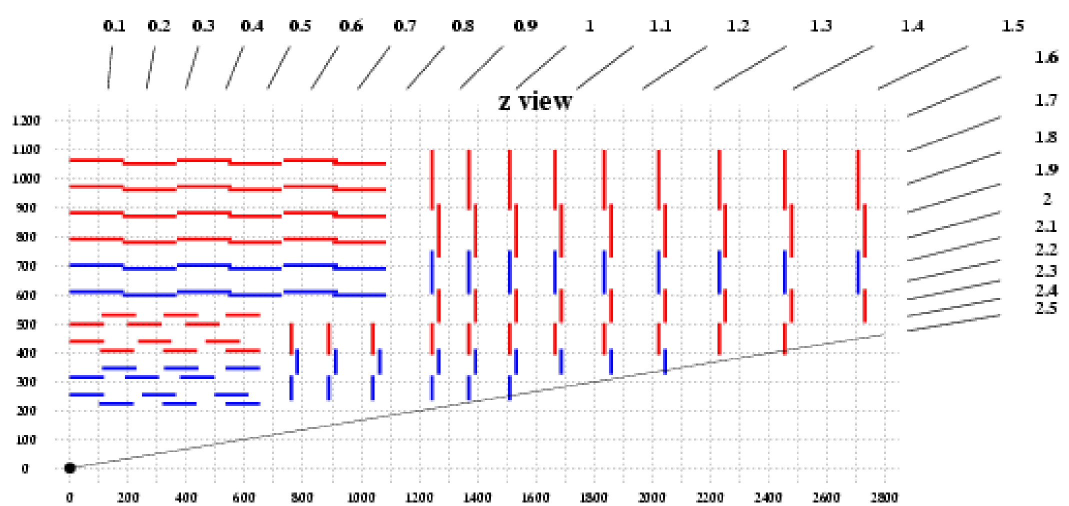
18.4k ch



CMS

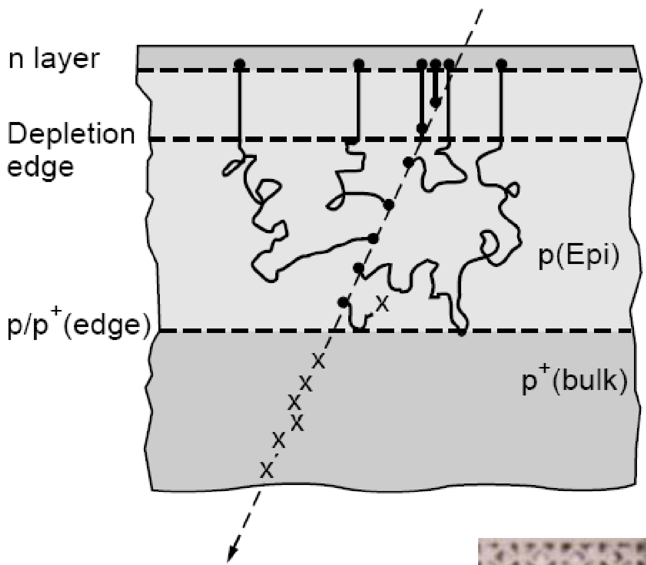
9.6M ch





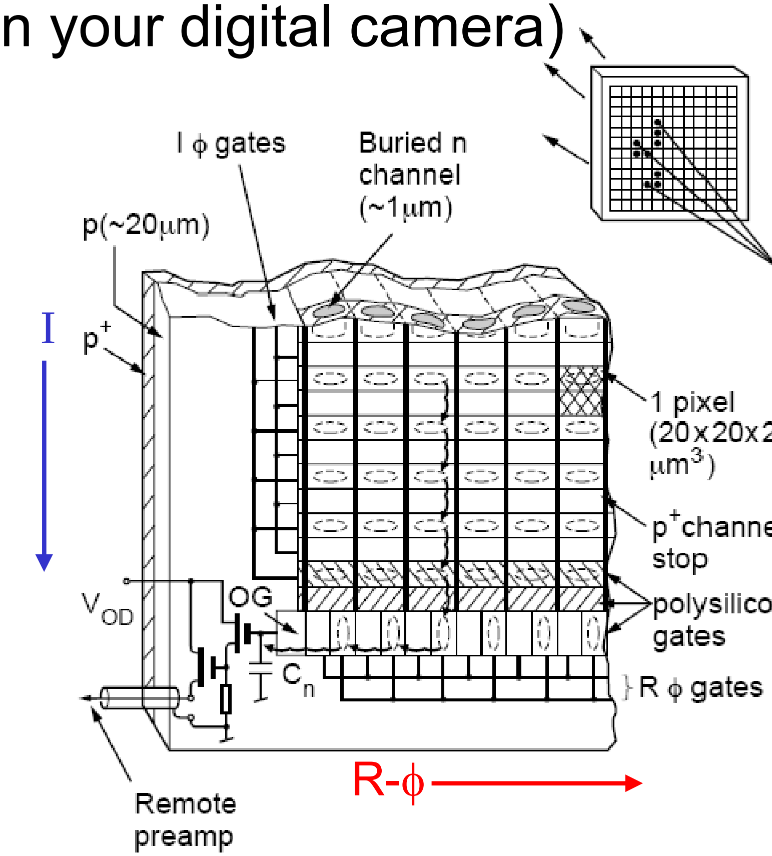
SSTDs: Pixels

- CCDs (charge-coupled devices) (what's in your digital camera)
  - how do they work?



Thin depletion layer; active p-type epitaxial layer of ~20μm; generated charge reflected off of p$^+$ substrate and eventually collected

C. Dammerell



Complicated pixel structure built on surface; Readout is serial – I shifts move each row down, R-ϕ shifts read out the columns. Can take 100ms to read out a large detector

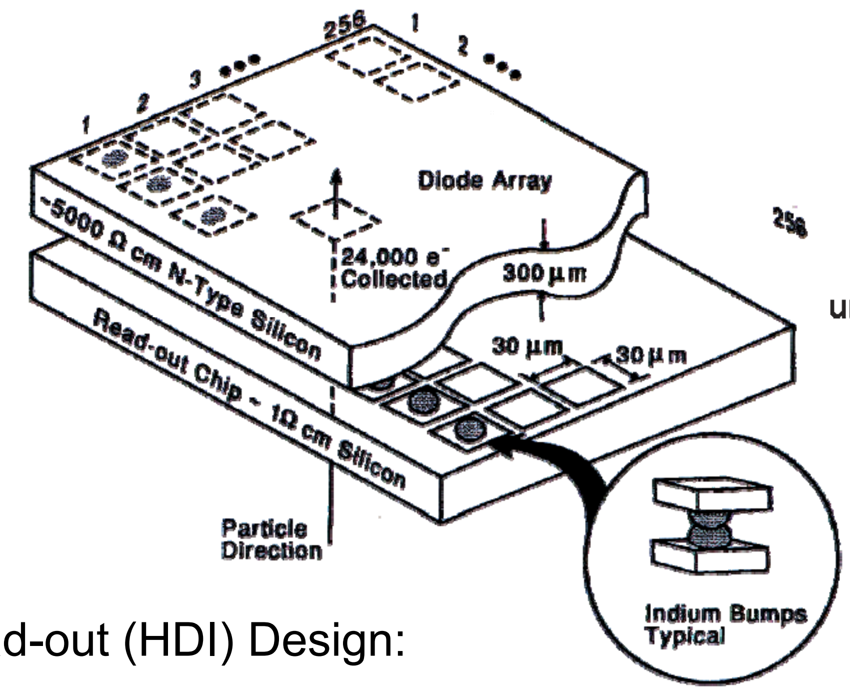
technology still advancing...

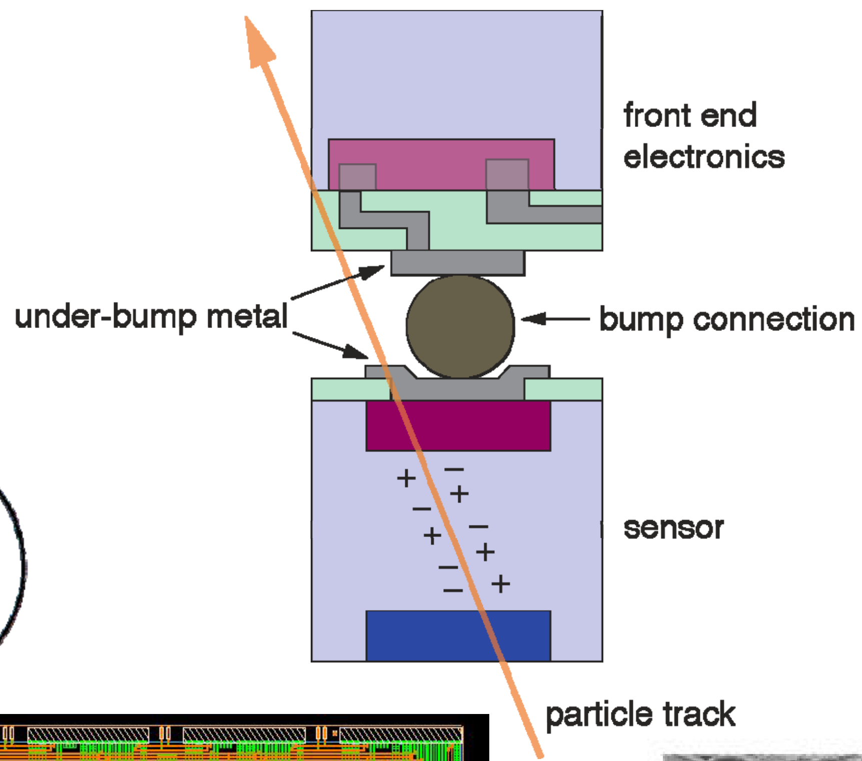
SLD VXD3:

- $3x10^8$ pixels
- world-record for collider detector hit resolution: ~4μm

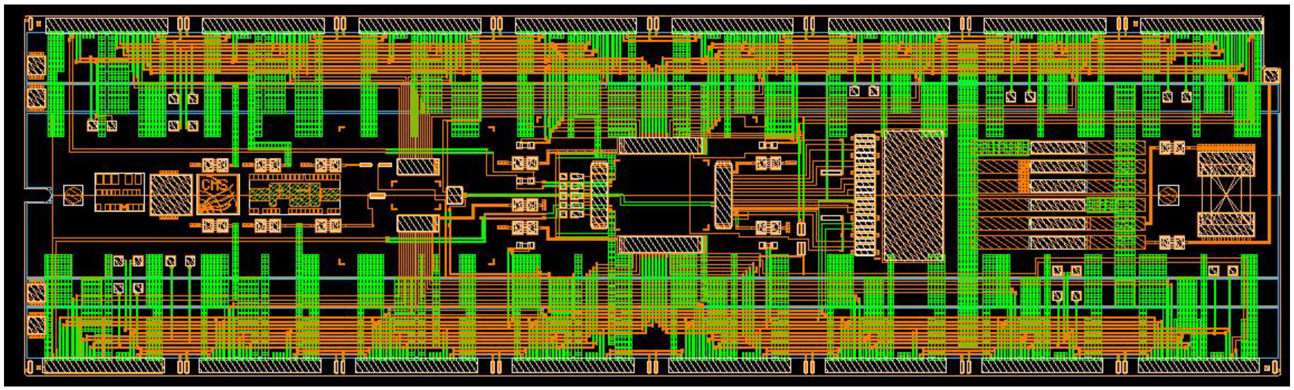
SSTDs: Hybrid Pixels

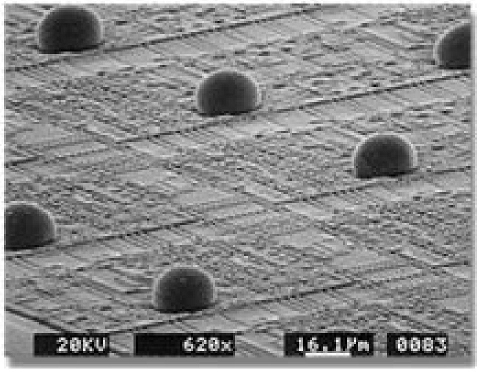
- Use fast, intelligent, rad-hard devices for high-occupancy environments
  - sensors separate from readout electronics – bonded together





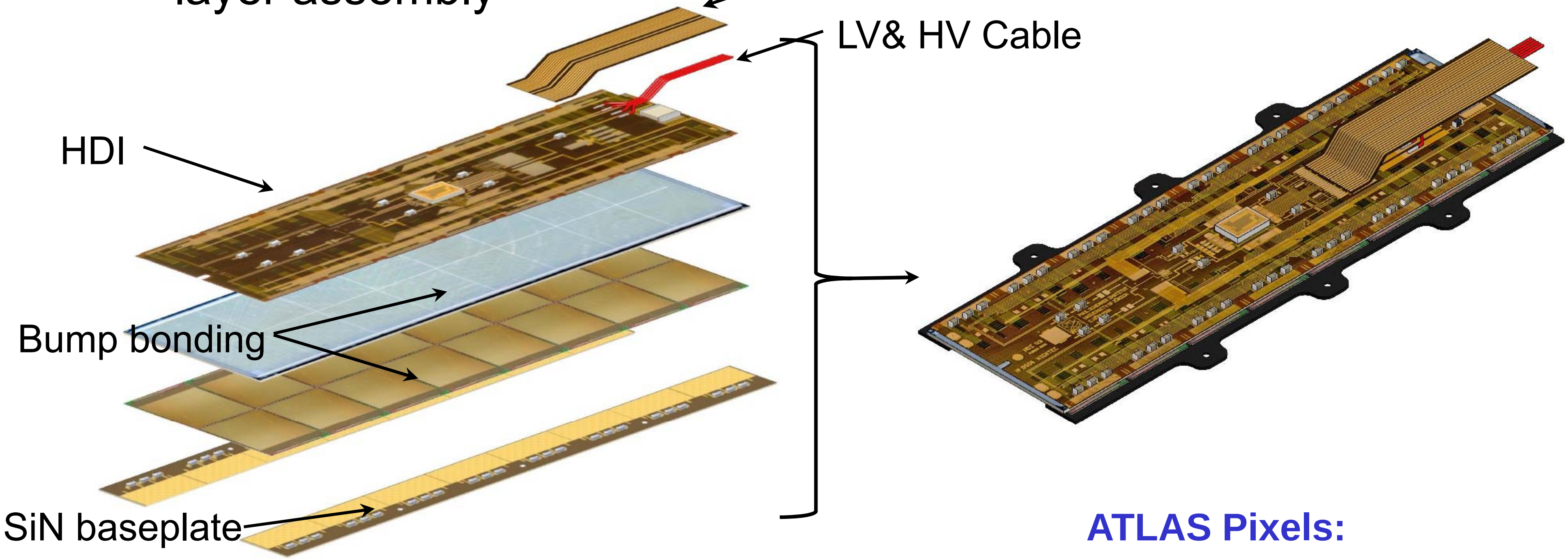
Read-out (HDI) Design:





Pixel Modules and systems

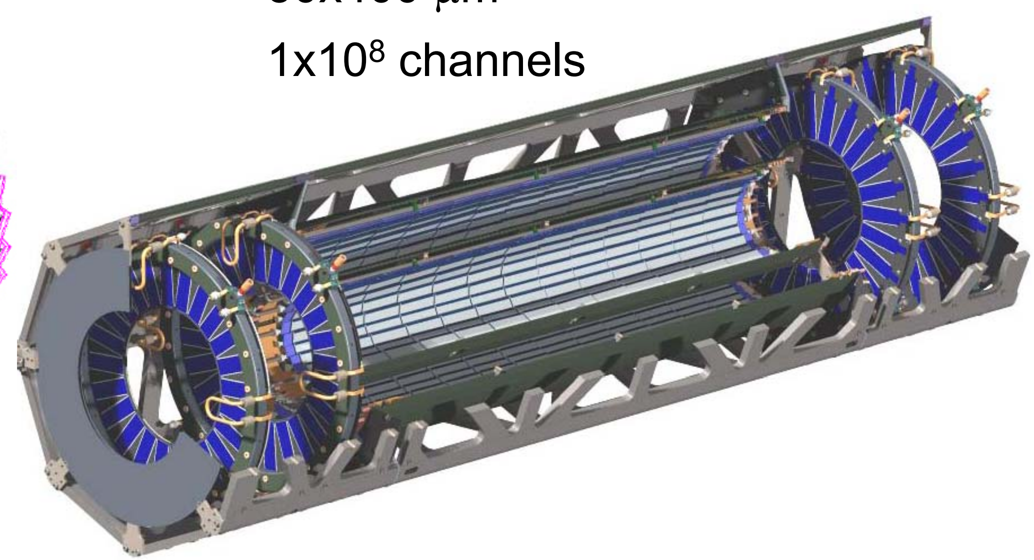
- layer assembly



ATLAS Pixels:

50x400 μm

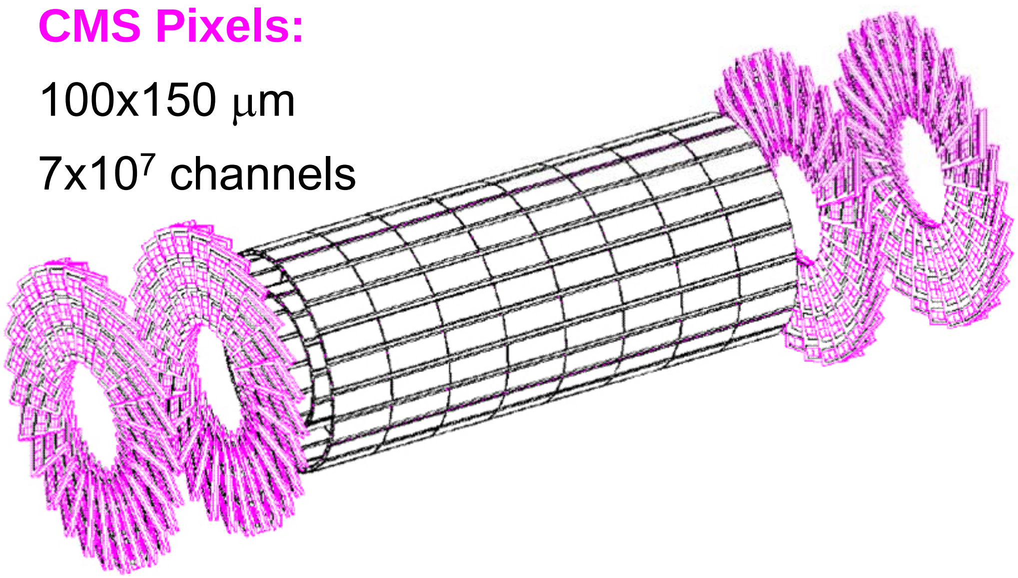
$1x10^8$ channels



CMS Pixels:

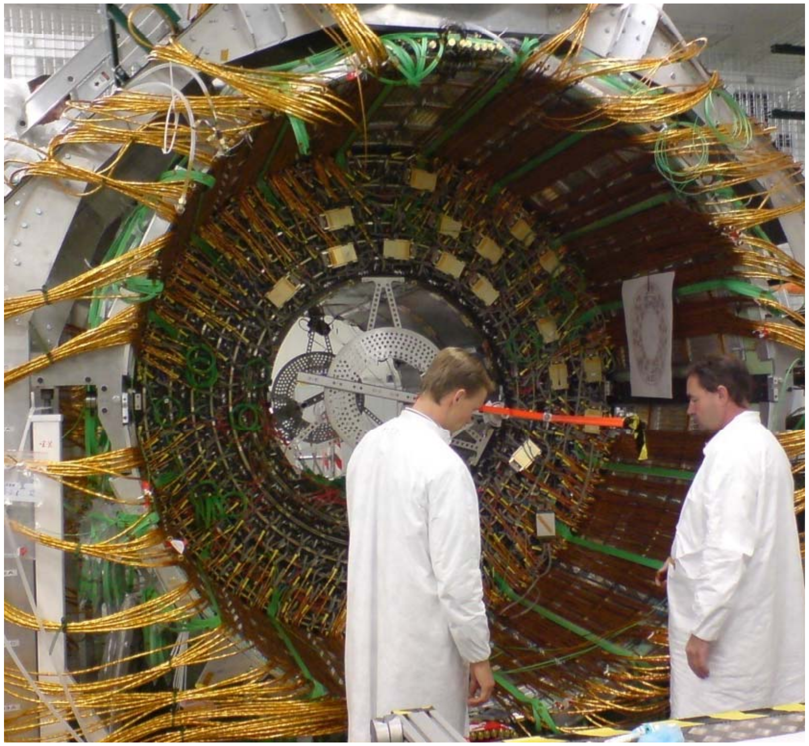
100x150 μm

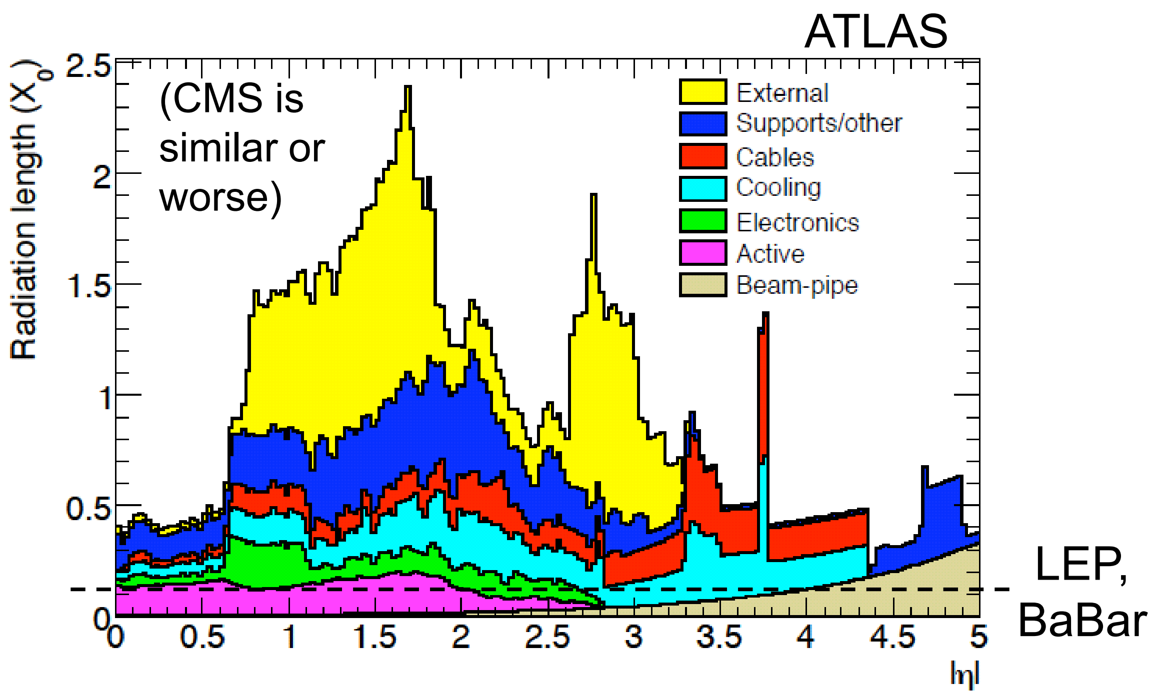
$7x10^7$ channels



SSTDs: Issues

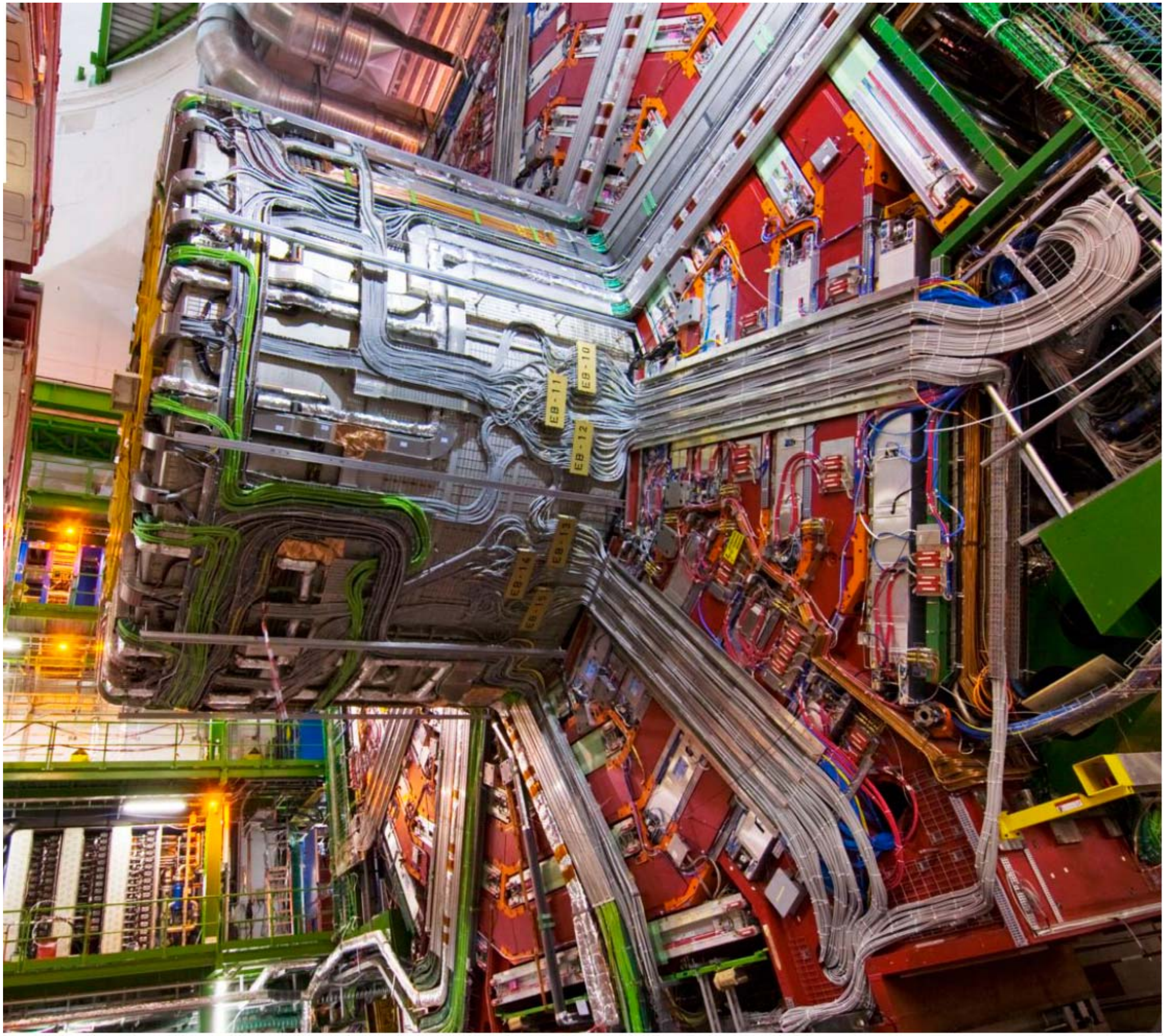
- Support infrastructure
  - even with miniature electronics, lots of power dissipated
    - cooling necessary in active volume
  - detectors tend to be “thick” – lots of material from supports, sensors





- $$$/μm³
  - even with miniaturization, channels cost money

SSTDs: "services"



Tracking Vocabulary

- "track" : a parametric representation of a charged particle's trajectory
  - usually calculated from the positions of hits in one or more particle detectors assumed to come from a single particle traversing their sensitive areas
- "hit" : a signal or group of adjacent signals in a single layer of a tracking detector that originates from the passage of a single charged particle. Also often called a "cluster"
- "error" : the expected resolution of a hit.
  - can vary with the angle of incidence of the track, the number of hit elements, drift time, etc.
- "pattern recognition" : the process of selecting a group of hits from different layers of a tracking detector that is geometrically consistent with originating from a single charged particle
  - the hardest part of tracking, algorithmically

Tracking Vocabulary

- "fitting" : the process of calculating the parameters of the particle's trajectory using the hit positions and errors
  - can be done iteratively or in a single pass through the hits collected by the pattern recognition algorithm
- "error matrix" : the (usually) 5x5 covariance matrix that gives the uncertainties on the track parameters
- "multiple scattering" : the inevitable deviation of particle paths from a perfect curve caused by coulomb interactions with matter
- "energy loss" : ionization loss caused by interactions of the charged particle with the matter of the detector and ancillary material

Track Parameters

- When tracking in a solenoidal magnetic field, particle trajectories are assumed to be helical, at least locally
  - 5 (or 6) parameters needed to define the trajectory
    - several choices possible
    - some better than others for things like high-precision vertexing or extrapolation several meters to outside detectors
    - round-off or numerical precision errors can play a role
  - a common parameterization is to use
    - $(c, \phi_0, d_0, \lambda, z_0)$, where

      c = ½ R, where R is the radius of curvature

      ϕ_0 is the direction of the track at the closest point to (0,0)

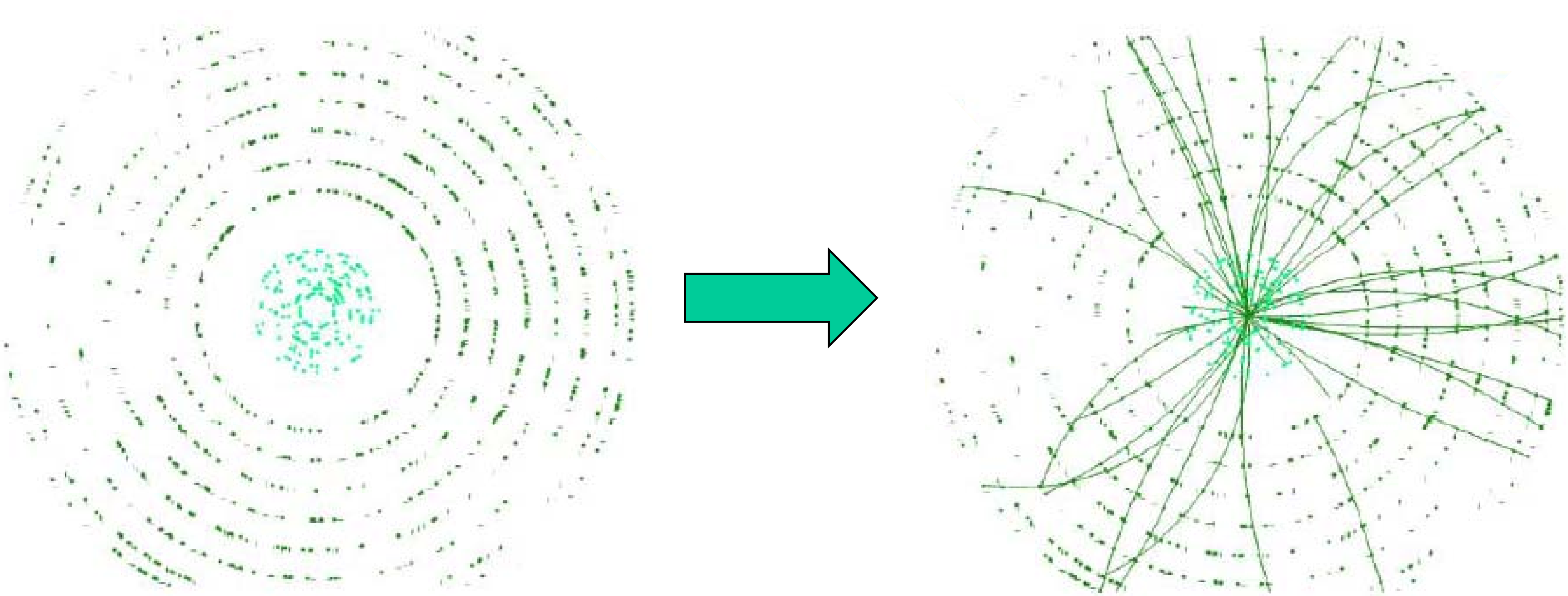
      d_0 is the distance of closest approach to $(x = 0, y = 0)$

      λ is $\cot\theta$, θ = polar angle measured up from beam axis

      z_0 is the z position of the track when it is at its distance of closest approach to $(x = 0, y = 0)$

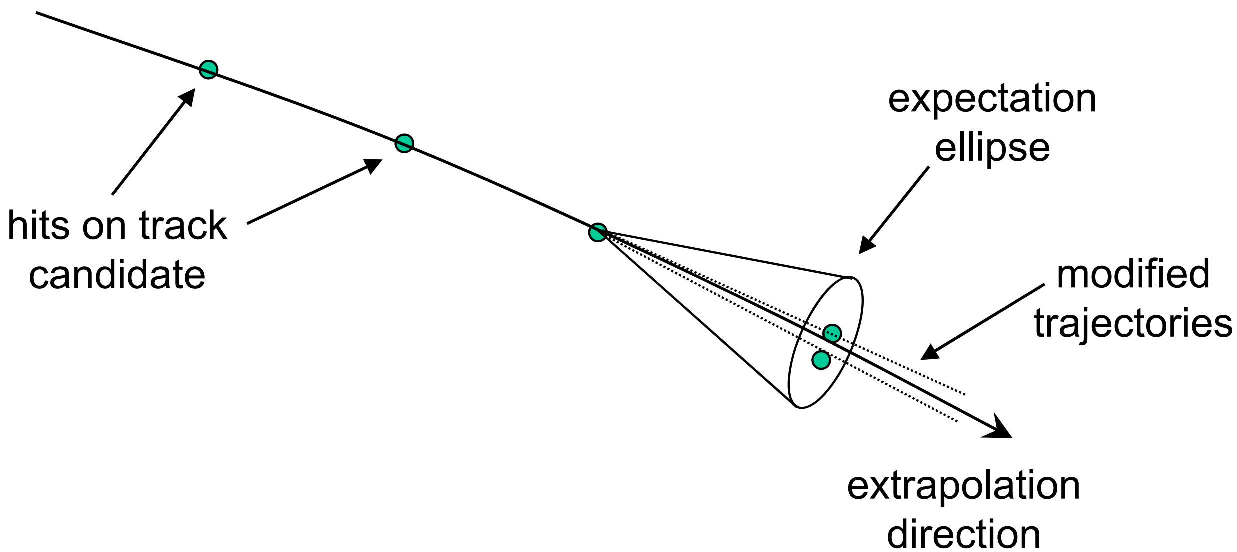
Tracking: Steps

- First, have to find track candidates:
  - "Pattern Recognition"
- Then (or simultaneously) we need to estimate the track parameters
  - "Fitting"
- The Trick:



Pattern Recognition: Road-Following

- Simplest to understand, not optimal in some cases
- Subset of well-separated hits (and possibly a beam spot) are used to create initial track hypotheses
- Candidate tracks are extrapolated to next detector layers to add potential new hits, refine track parameters, continue

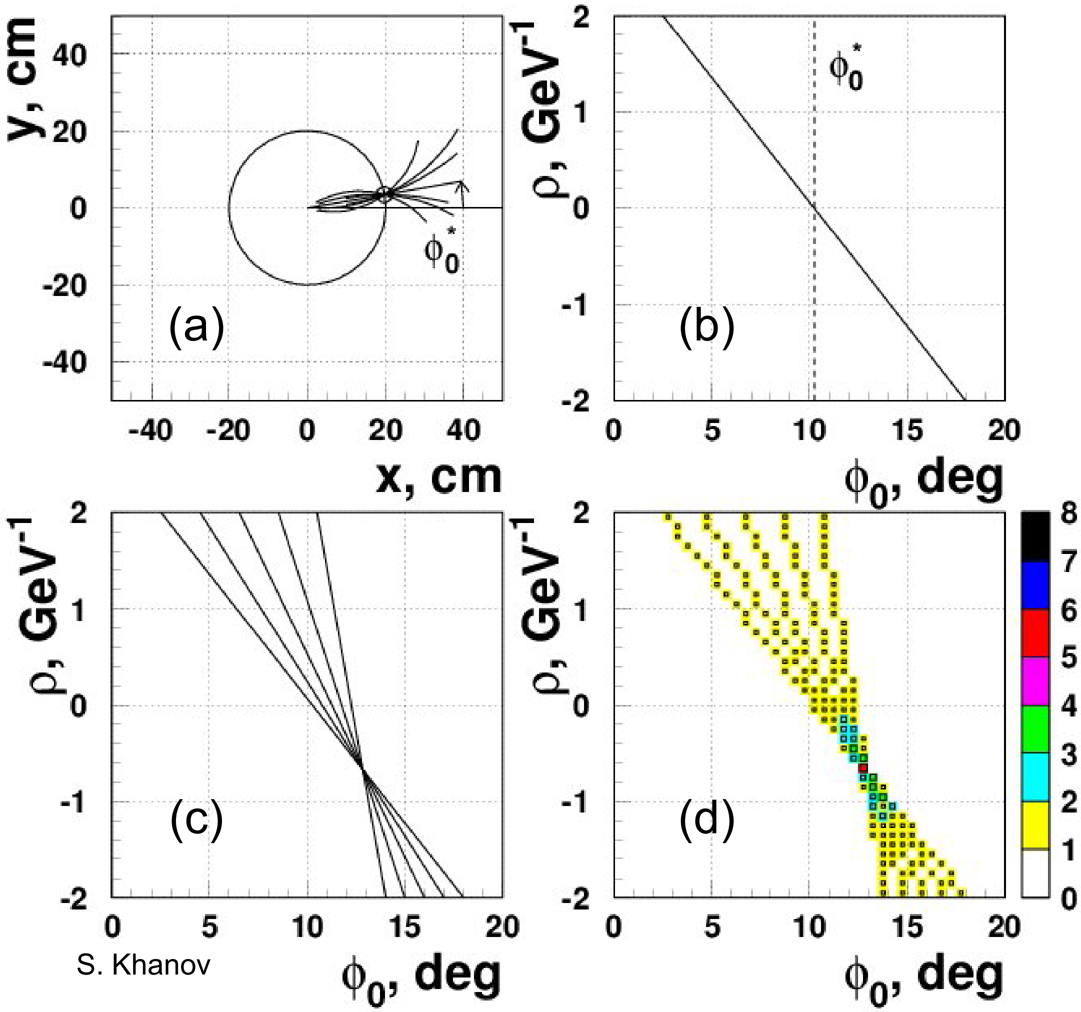


- Viable as long as branching is controlled (by truncation, by low occupancy, or by superior hit/parameter resolution)

Pattern Recognition: Hough Transform

Paul Hough, 1962

- Simultaneously test all track hypotheses for all possible hits
- Set up an accumulator that records a list of all possible track hypotheses for a given hit: each (x,y) point (a) corresponds to a line in (ρ,ϕ_0) space, where ρ is curvature, and ϕ_0 is the initial angle (b)



- each hit on the track corresponds to a different line in $\rho-\phi$ space (c)
- if the plane is divided up into bins (d), the bin containing the maximum number of track contributions gives the correct common track parameters
- can be made more clever by adapting bin size, etc.
- generally used to select hits

S. Khanov

UNIVERSITY OF NOTRE DAME

Track Fitting: Least Squares

following P. Avery

- Generic problem is to take a set of measurements y_l and use them to estimate a set of track parameters α such that $y_l = f_l(\alpha)$. If we take an initial guess α_A at the parameters and make a linear expansion around that solution, we get

$$y_l = f_l(\alpha_A) + (\partial f_l / \partial \alpha_i)(\alpha_i - \alpha_{A\,i})$$

- This allows us to define a χ^2 measure

individual measurement errors

$$\chi^2 = \sum_l (y_l - f_l(\alpha_A) - A_{li}(\alpha_l - \alpha_{A\,l}))^2 / \sigma_l^2$$

$$= (\mathbf{y} - \mathbf{f}(\alpha_A) - \mathbf{A}(\alpha - \alpha_A))^T \mathbf{V}_y^{-1} \, (\mathbf{y} - \mathbf{f}(\alpha_A) - \mathbf{A}(\alpha_A - \alpha))$$

$$\equiv (\mathbf{\Delta y} - \mathbf{A}(\alpha - \alpha_A))^T \mathbf{V}_y^{-1} \, (\mathbf{\Delta y} - \mathbf{A}(\alpha - \alpha_A))$$

where $\mathbf{\Delta y} = \mathbf{y} - \mathbf{f}(\alpha_A)$ and $A_{li} = \partial f_l(\alpha)/\partial \alpha_i|_{\alpha_A}$ is a matrix of constant derivatives. $\mathbf{V}_y$ is the covariance matrix of the measurements.

Track Fitting: Least Squares

- We want the parameter estimation that minimizes the distance between the measured points and the fitted track, so we set $\partial\chi^2/\partial\alpha_i = \mathbf{0}$ which gives us the solution

covariance matrix of α

$$\alpha = \alpha_A + \mathbf{V}_A \mathbf{A}^T \mathbf{V}_y^{-1} \Delta \mathbf{y} \quad \text{where} \quad \mathbf{V}_A = (\mathbf{A}^T \mathbf{V}_y^{-1} \mathbf{A})^{-1}$$

Ideally, one iterates to get the best estimate of the parameters α

- This method has several problems:
  - it only works well if all of the points are independent
    - many correlated points require inversion of a huge matrix
  - all of the points have equal weight
    - democratic, but not physical
  - Unfortunately, Multiple Scattering and Energy Loss introduce correlations between one hit and the next
    - $\mathbf{V}_y$ is not diagonal
    - closest hits contribute most to determination of local track parameters

Kalman Filter

Kalman, 1960, Billoir, 1984

- An alternate method exists that allows sequential refinement of the track parameters while including Multiple Scattering and Energy Loss effects in the correct way. It is completely equivalent to the least-squares fit if these effects are small.
- Assume we have an initial estimate of track parameters α_1 and their covariance matrix $\mathbf{V}_{\alpha 1}$ at point 1. We can extrapolate these to point 2, and do it correctly, if we modify α_1 by adding energy loss $(\alpha_1 \rightarrow \alpha_1')$ and modify the covariance matrix by putting in MS and Eloss $(\mathbf{V}_{\alpha 1} \rightarrow \mathbf{V'}_{\alpha 1})$. The new χ^2 can be written

$$\Delta\chi^2 = (\mathbf{\Delta y}_2 - \mathbf{A}_2(\alpha_2 - \alpha_1'))^T \mathbf{V}^{-1}_{\mathrm{meas}\,2}(\mathbf{\Delta y}_2 - \mathbf{A}_2(\alpha_2 - \alpha_1'))$$

$$+ (\alpha_2 - \alpha_1')^T \mathbf{V'}^{-1}_{\alpha 1}(\alpha_2 - \alpha_1')$$

incorporates new point 2 measurements

pulls of track parameters away from previous fitted values

- As before, $\mathbf{\Delta y}_2$ is the vector of residuals before the fit, and $\mathbf{A}_2$ is the matrix of track parameter derivatives evaluated at Point 2.

Kalman Filter

- we can solve for the minimum in the χ^2 the same way, yielding

$$\alpha_2 = \alpha_1' + \mathbf{V}_{A\,g}\mathbf{A}_2^T\mathbf{V}_{\text{meas}\,2}^{-1}\mathbf{\Delta y}_2$$

$$\mathbf{V}_{\alpha\,2} = \mathbf{V}_{A\,g} = \mathbf{V'}_{\alpha\,1}(1 + \mathbf{A}_2^T\mathbf{V}_{\text{meas}\,2}^{-1}\mathbf{A}_2\mathbf{V'}_{\alpha\,1})^{-1}$$

incorporates info from previous point

- With some matrix trickery, and if only one measurement is being added, things get much simpler:

$$\alpha_2 = \alpha_1' + \mathbf{V}_{A\,g}\mathbf{A}_2^T\frac{\delta y_i}{\sigma_i^2},$$

$$\mathbf{V}_{\alpha\,2} = \mathbf{V}_{A\,g} = \mathbf{V}_{\alpha\,1} - \frac{\mathbf{V}_{\alpha\,1}\mathbf{A}_2^T\mathbf{A}_2\mathbf{V}_{\alpha\,1}}{\sigma_i^2 + \mathbf{A}_2\mathbf{V}_{\alpha\,1}\mathbf{A}_2^T}$$

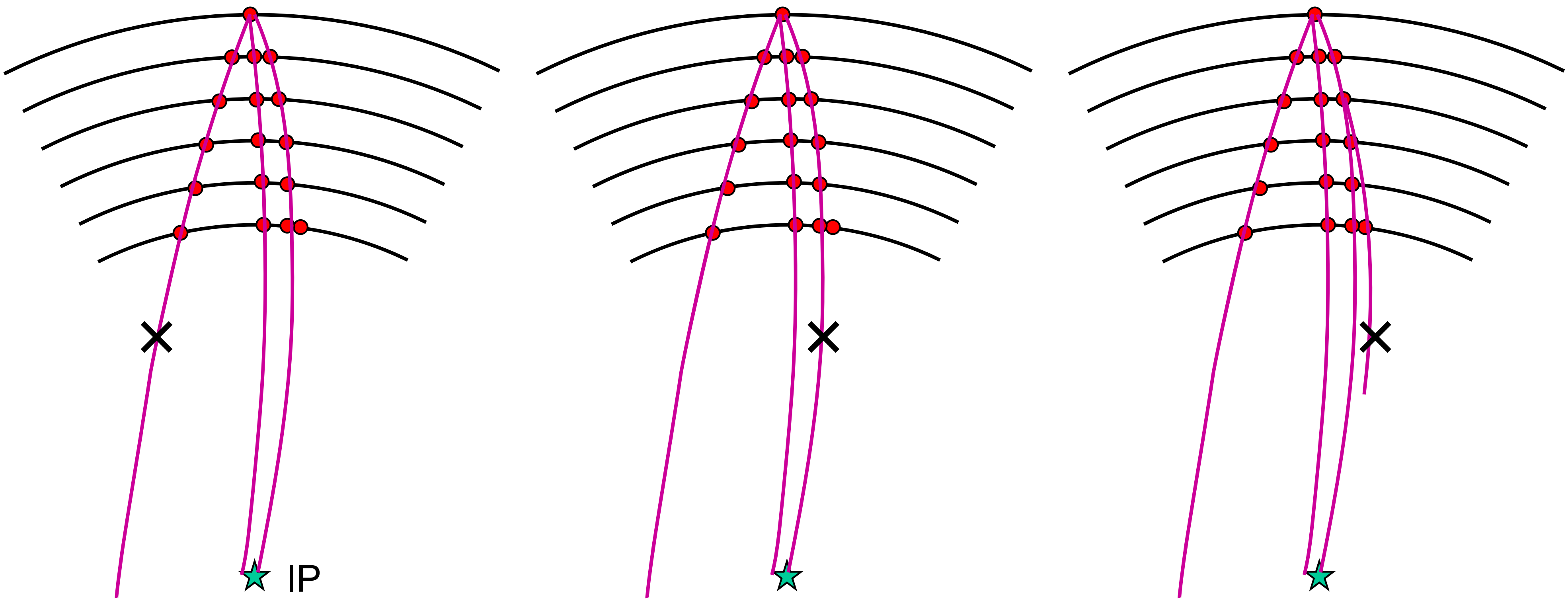
- no matrix inversion needed! Can be very fast...

Kalman Filter

- Uses all of the information $\Rightarrow$ gives optimal fit
- Traces track parameters from one end to the other
  - best determination is always where it finishes
  - "Smoothing" step sometimes necessary if one wishes to extrapolate somewhere from other end of the track
    - start with optimal parameters at one end, run filter backwards
- Fast: adding single hits one at a time can be done with minimal calculation
- (Note: can be used in pattern recognition in conjunction with the Road-following algorithm)
- Can also be used when Multiple Scattering and Energy loss are large (ATLAS & CMS)
- Comment: who would have thought major advances in track fitting algorithms could happen as late as the '80s and '90s?

Truncations and Modifications

- In general, generic track finding fails miserably in high-occupancy environments
  - too many fakes, or takes way too long…
- Compromises to efficiency are necessary to speed things up:



Only find tracks that originate near the IP

Only find higher momentum tracks (min p_T cut)

Limit number of missed layers and/or extrapolation residual

Comments on Pattern Rec., Fitting

- The name of the game is minimizing CPU consumption
  - any old algorithm will eventually work
    - days/event isn't tenable...
    - design considerations paramount in quest for speed
    - "generic" is almost never optimal
  - compromises in efficiency for speed are sometimes necessary
    - there is no perfect algorithm
  - speed optimization by mathematical trickery is a good thing
    - cleverness always preferred to brute force
  - algorithm implementation is also crucial
    - the optimal algorithm can still be poorly coded
- Oh, yeah, it has to be efficient, too, i.e., find all of the tracks
  - usually the easy part...
  - unless you worry about fakes in high-occupancy environments…

Designing Tracking Systems

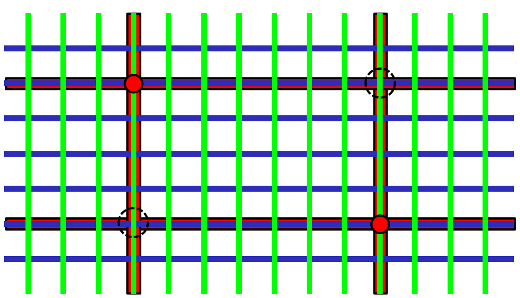
- Previously, we had an expression for momentum resolution:

$$\left.\frac{\sigma(p_T)}{p_T}\right|^{meas.} = \frac{\sigma_x \cdot p_T}{0.3 \cdot BL^2}\sqrt{720/(N+4)}$$

  – where N is the number of hits with resolution σ_x transverse to the particle direction

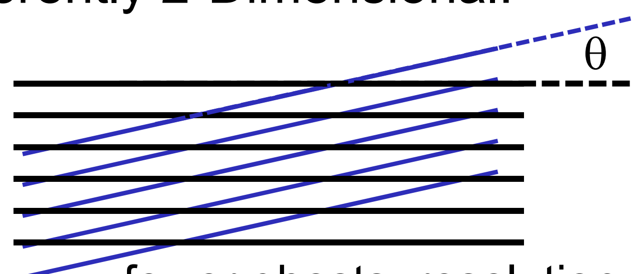
- Of course, transverse momentum (p_T) isn't the only coordinate!
  – in order to reconstruct a 4-vector, we need to measure the *entire trajectory* as precisely as possible
  – in particular, we need some measurement of the z position (along the beam direction) along the trajectory to get z_0 and λ
  – can be tricky: most of our detectors are inherently 2-Dimensional:

e.g. r-z silicon using double-metal: each hit generates ghosts (N!)



full resolution on z

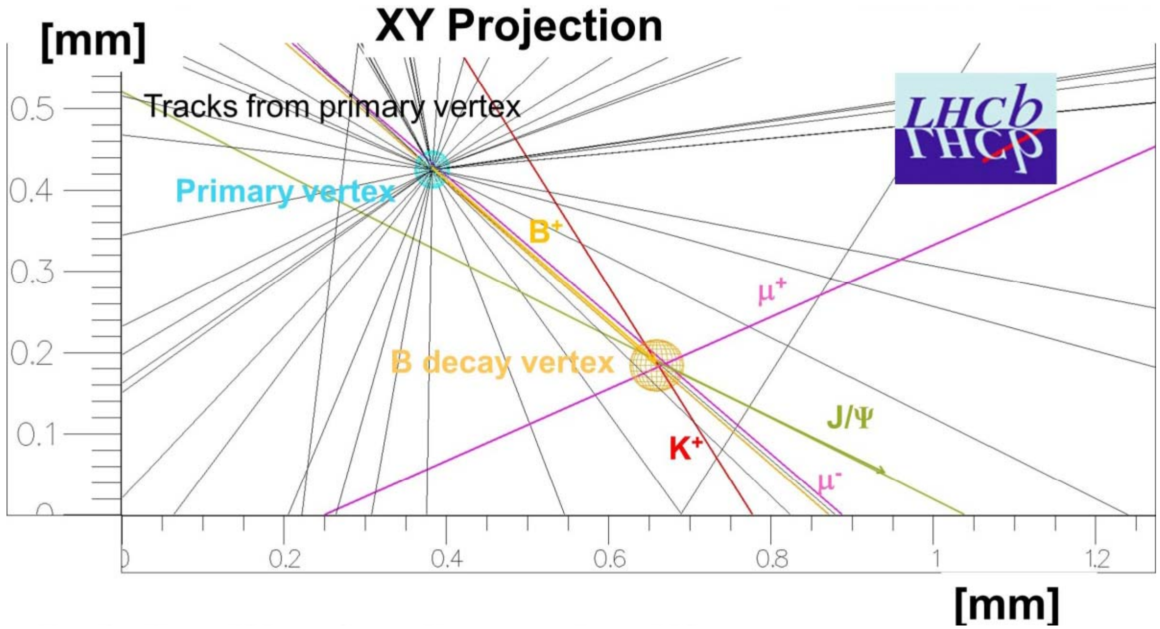
or two strip detectors glued with small stereo angle θ

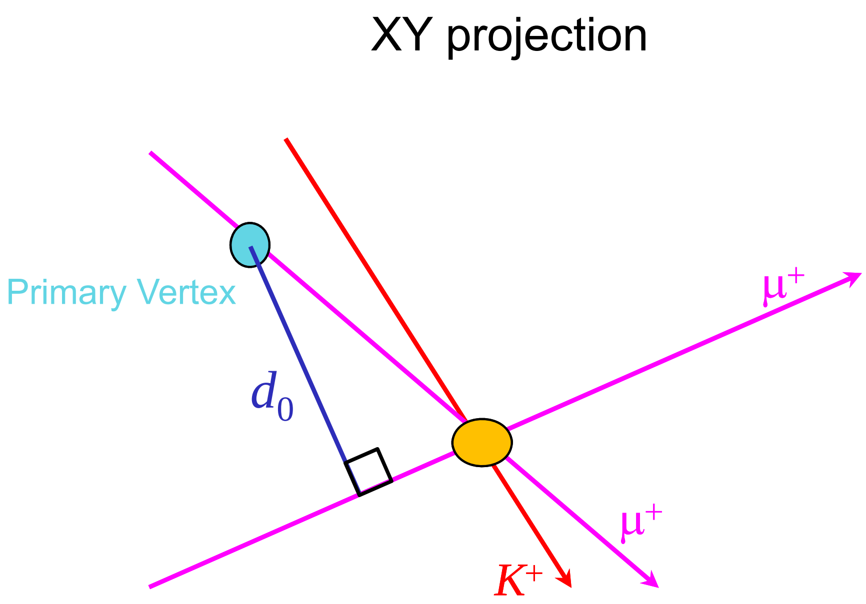


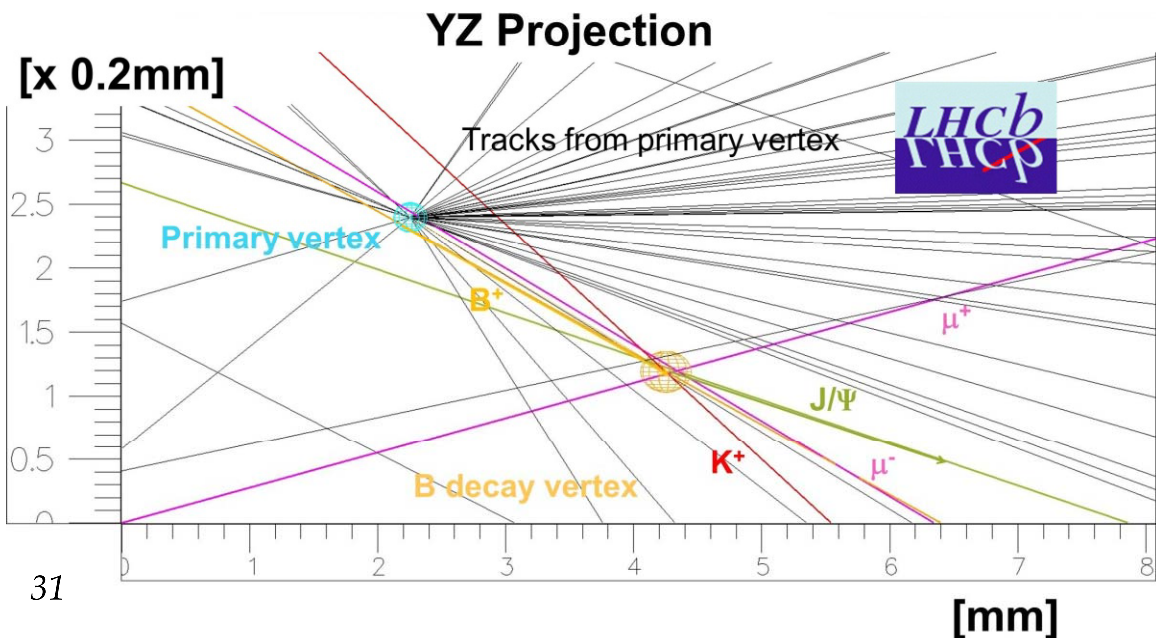
fewer ghosts; resolution on z degrades as $1/\sin\theta$

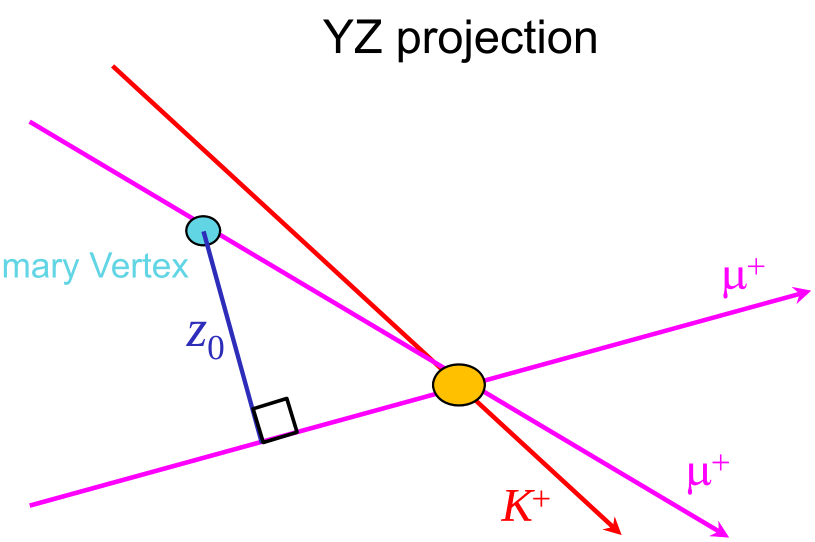
Impact Parameter Measurement

- Physics Example: $B^{+} \rightarrow J/\Psi K^{+}$









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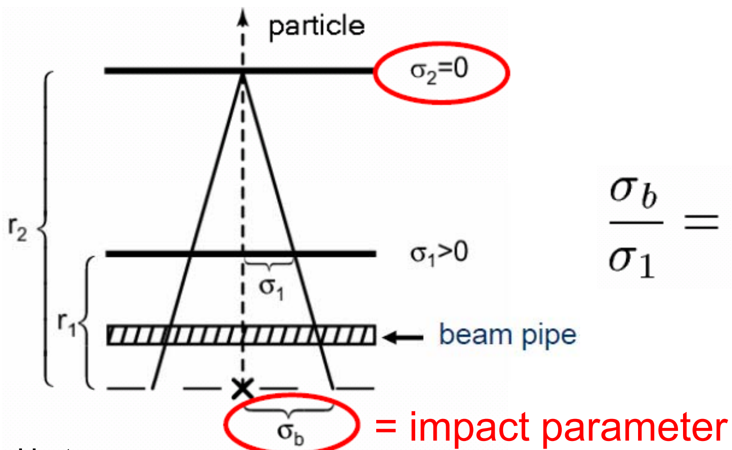
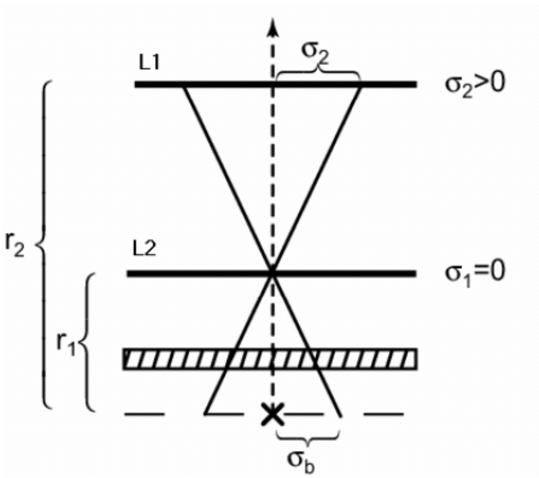
Impact Parameter Measurement

- Distance of closest approach to Primary Vertex must be measured precisely enough to observe secondary decays
  - *B* lifetime ~1.6 ps ⇒ $\gamma c \tau_B = \gamma \cdot 500\ \mu\text{m}$
  - generally accomplished by adding high-precision measurements (in *xy* and *rz*) as near to the interaction point (beampipe) as possible



from G. Herten



$$\frac{\sigma_b}{\sigma_1} = \frac{r_2}{r_2 - r_1}$$

make these as small as possible

$$\sigma_b^2 = \left(\frac{r_1}{r_2 - r_1}\,\sigma_2\right)^2 + \left(\frac{r_2}{r_2 - r_1}\,\sigma_1\right)^2 + \sigma_{MS}^2$$

implies thin beampipe

$$\frac{\sigma_b}{\sigma_2} = \frac{r_1}{r_2 - r_1}$$

Design Criteria

Physics-motivated, of course…

- Good Momentum Resolution
  - combination of large B, L
  - large N, or small σ_x to compensate
  - small number of radiation lengths (minimal material)
- Good Impact Parameter Resolution
  - thin/small beampipe
  - high-precision detectors very close to IP
- Good Efficiency
  - hermetic
- Robust against high occupancy
  - granularity (small effective detector size)
  - fast (information from ~few beam crossings at most)

Engineering Design Criteria

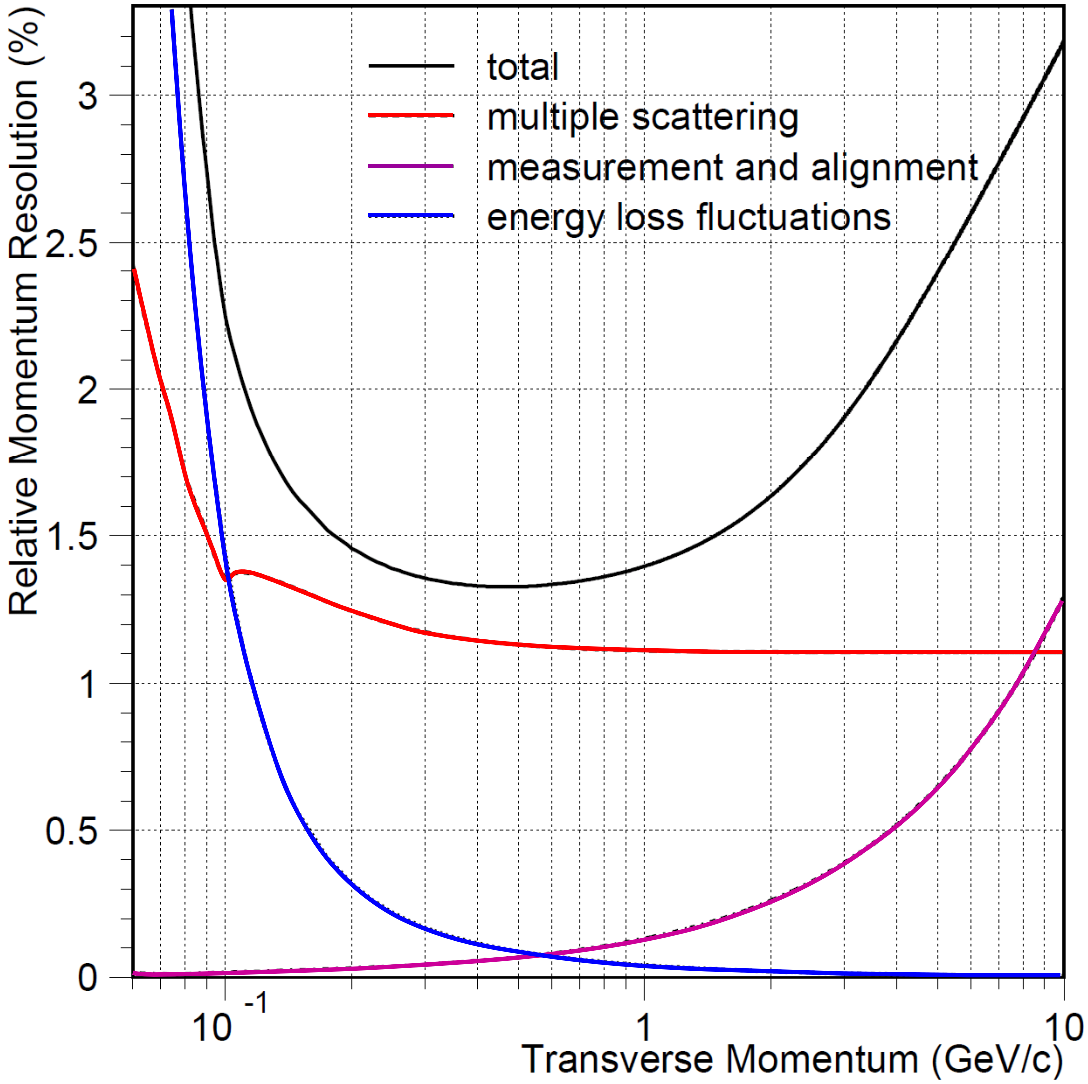
But you have to be able to build it!

Must also design for:

- Manageable System Size
  - $$$/channel
  - readout electronics, cables, etc.
- Support Structure
  - thermal and mechanical stresses
- Services
  - HV, cooling, data conduits, etc.
- Ease of installation/maintenance
- Radiation Hardness
- Redundancy
  - not quite a satellite launch, but these systems will need to survive for long periods in a harsh environment

Parameter Resolution Evolution

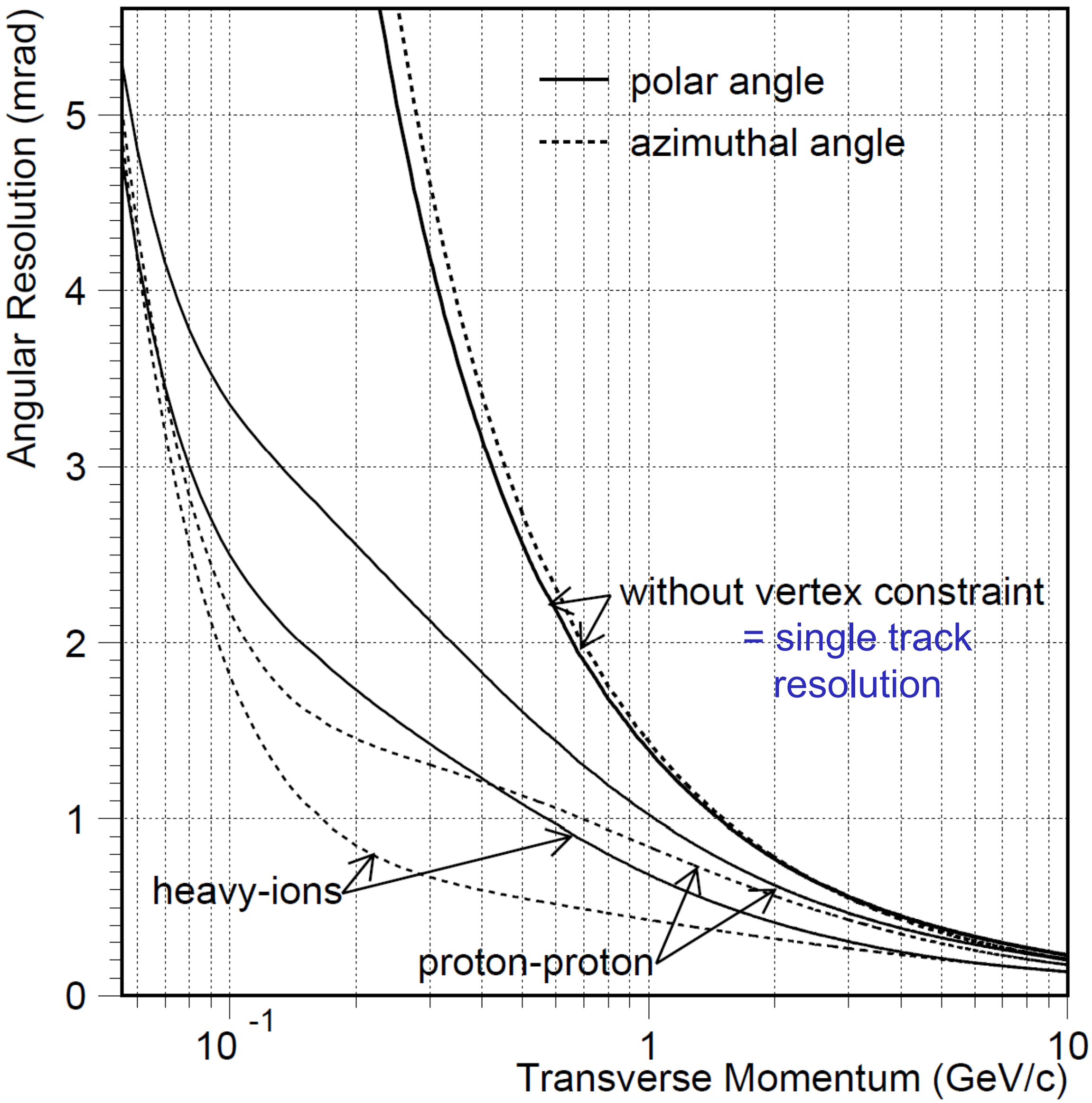
- From ALICE: study of momentum resolution budget



- As expected, MS and Eloss contributions scale as $1/\beta$ and $1/p_{\mathrm{T}}$, respectively
- Note that MS doesn't asymptotically approach zero
  - total amount of material *does* matter!
- Alignment/resolution effects dominate at high p_{T}
  - Why?

Parameter Resolution Evolution

- ALICE: Angular resolution with/without vertex constraint

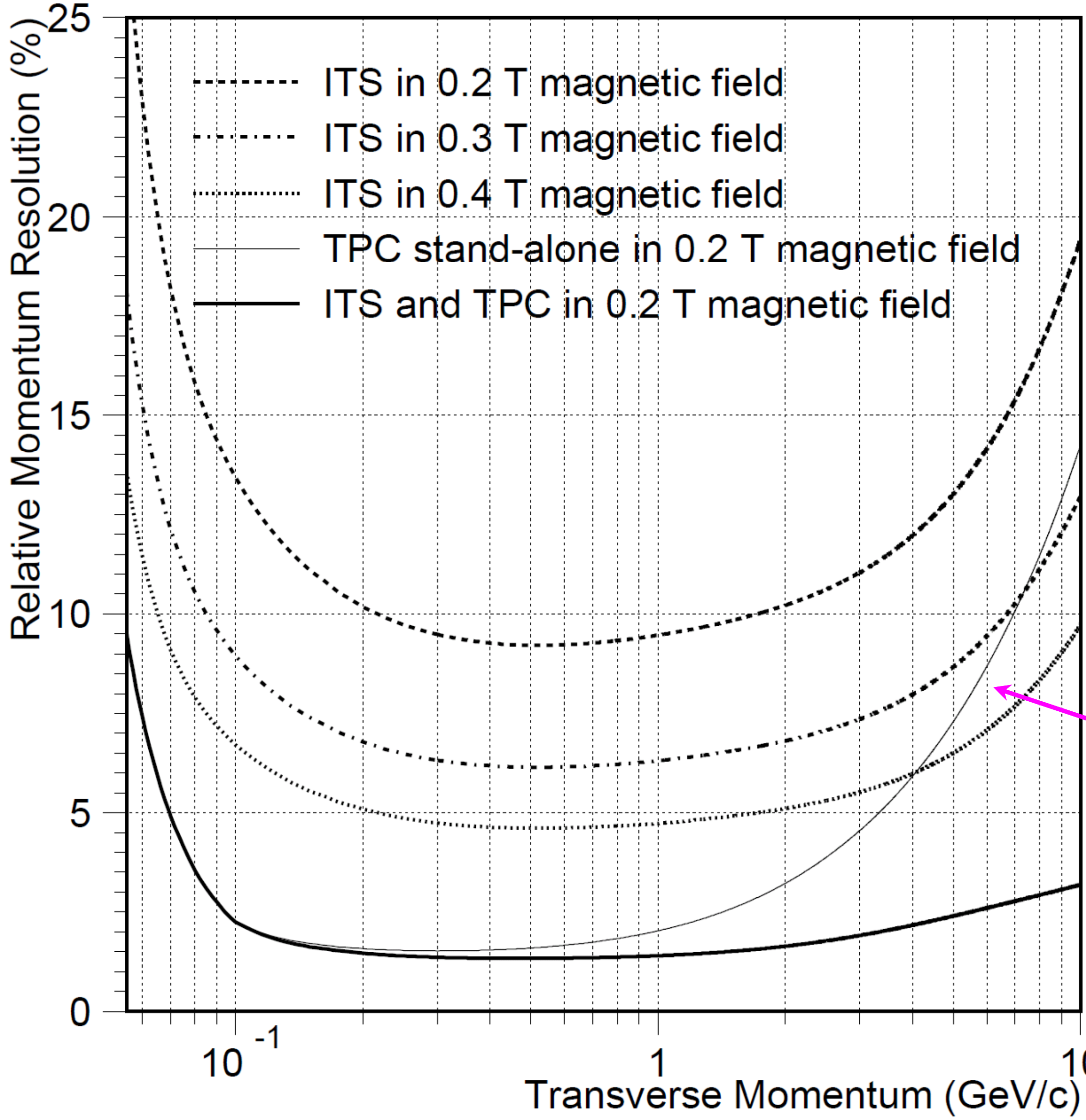


= constrain tracks to come from the found collision point for each event

- Same MS and Eloss effects determine angular resolution
- TPC geometry + Pixels insures that polar and azimuthal angles are measured equally well
- proton-proton vertex has less of an effect than heavy-ion
  - Why?
  - asymptotic vertex resolution only reached at about 1000 tracks/vertex!

Parameter Resolution Evolution

- ALICE: momentum vs. B field



Increasing B field improves p_T resolution as expected

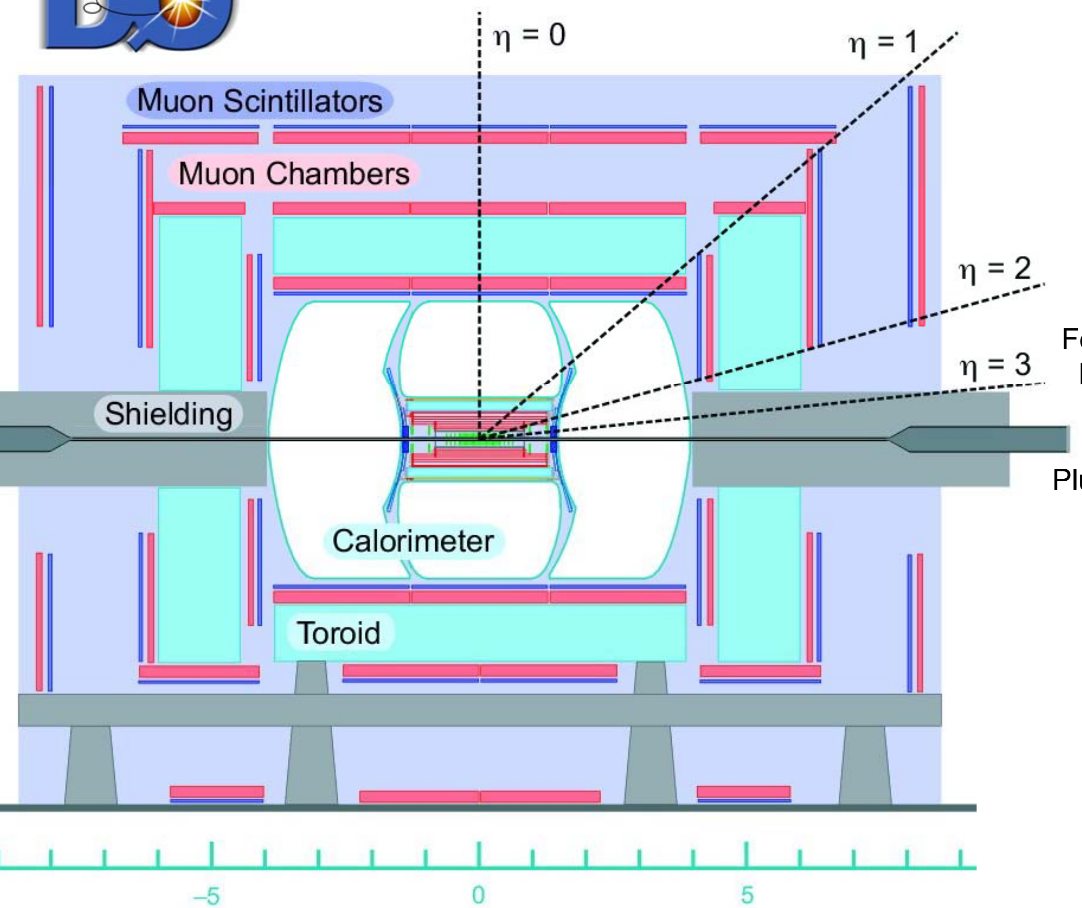
Additional measurements with superior position resolution of ITS dominate momentum error at high p_T

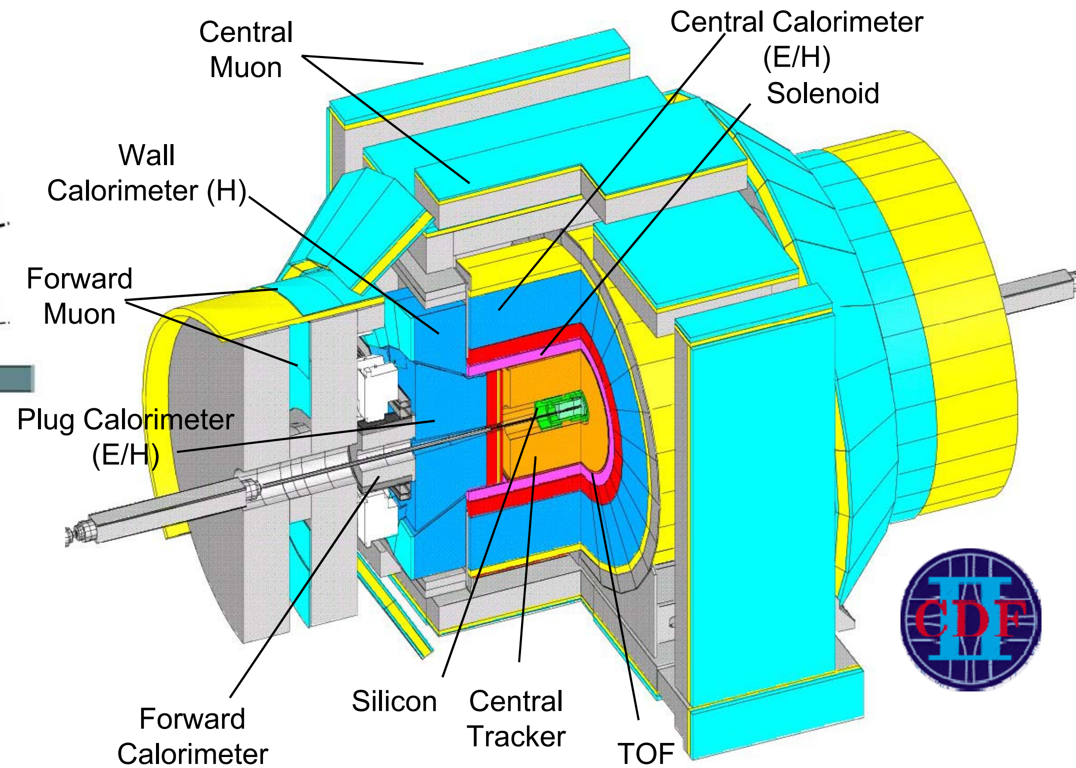
- extra measurements close to the origin constrain curvature

Tevatron Trackers

- Note: neither experiment at the Tevatron has pixels. Why?
  - Design choices frozen ~1997
  - hybrid pixel technology not mature at that time
    - or even to be considered for Run IIb upgrades

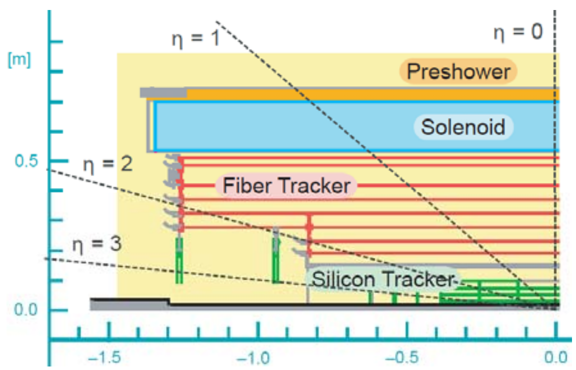
~ same scale:

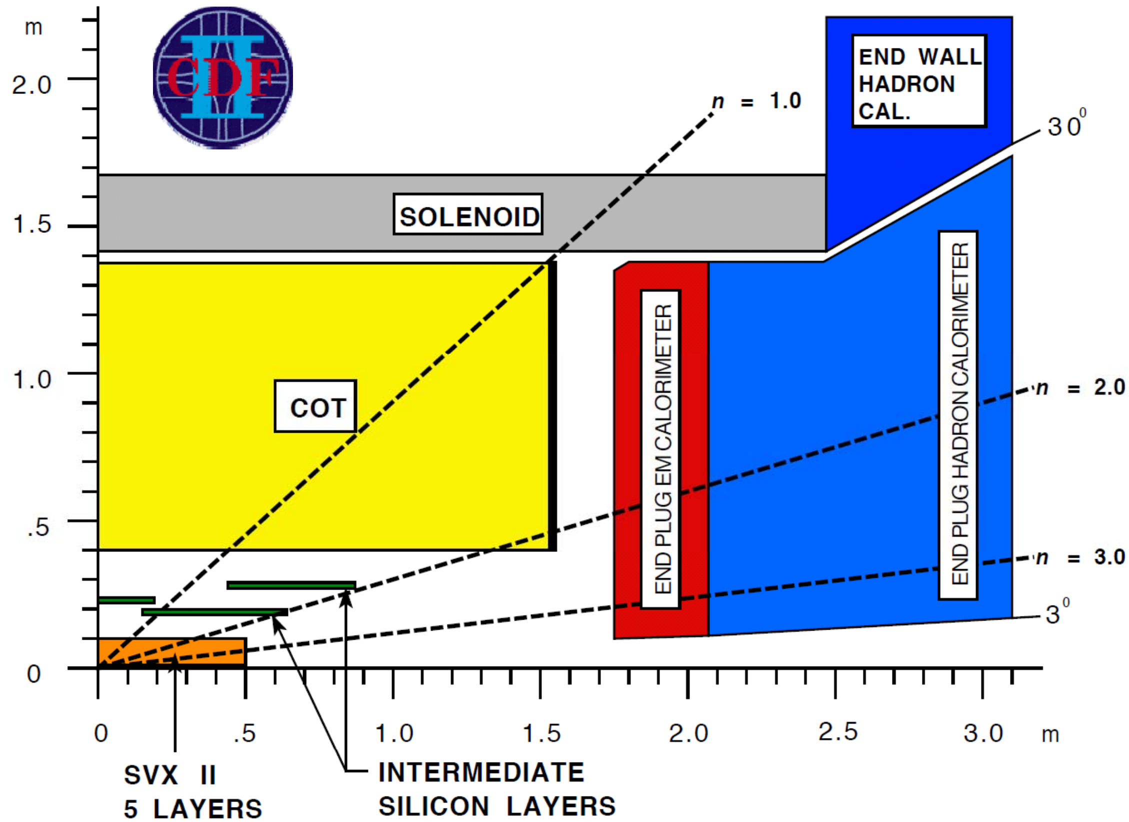




Tevatron Trackers

- Side-by-side comparison



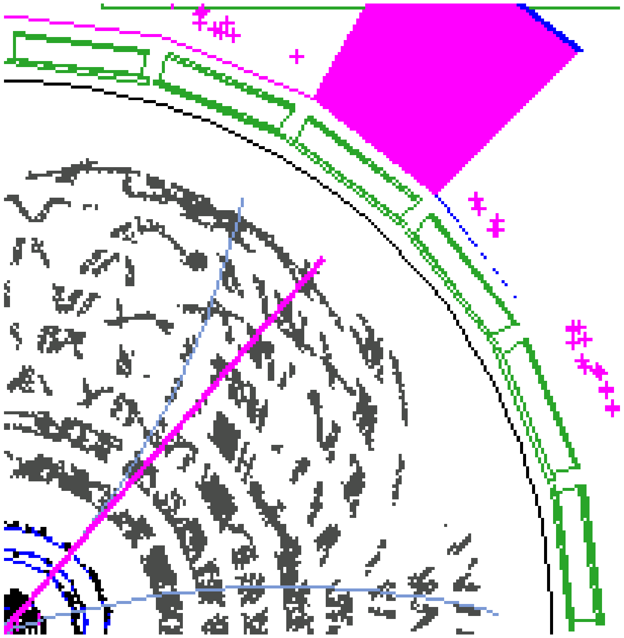


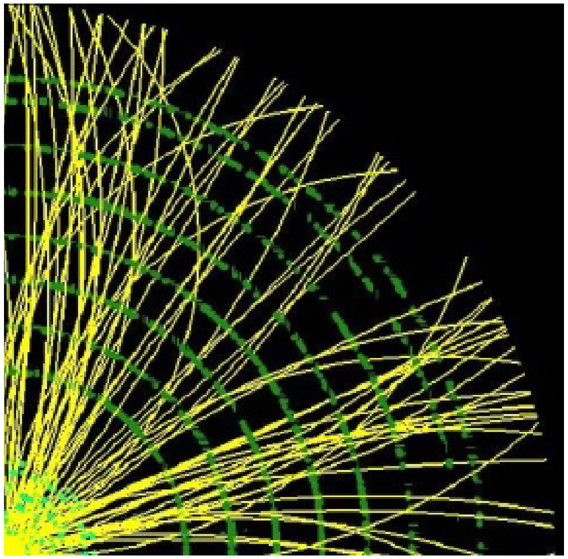
- Magnetic tracking: upgrade that had to fit in existing calorimeter
- 2T Magnetic Field
- maximum radius (L) = 0.52m
- length: ~2.5m

- large tracking volume
- 1.4T Magnetic Field
- maximum radius (L) = 1.37m
- length: ~3.1m

Tevatron Trackers

- Outer Trackers:





CDF Central Outer Tracker:

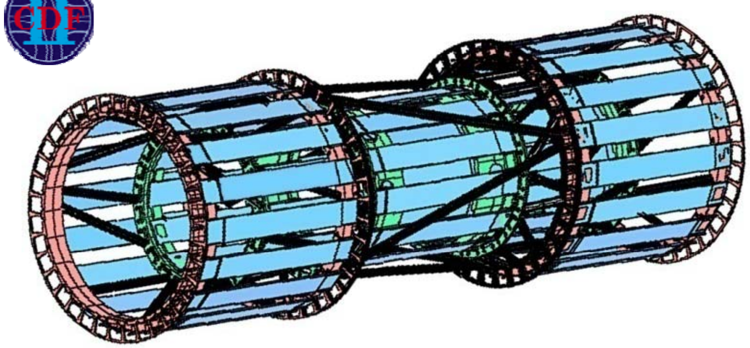
- 96 layers of sense wires
- single hit resolution 140μm
- full coverage $|\eta| < 1.0$
- $\sigma(p_T)/p_T = 0.15\% \times p_T\,(\mathrm{GeV})$
- combined with silicon, hit count plus large L gives superior track resolution overall

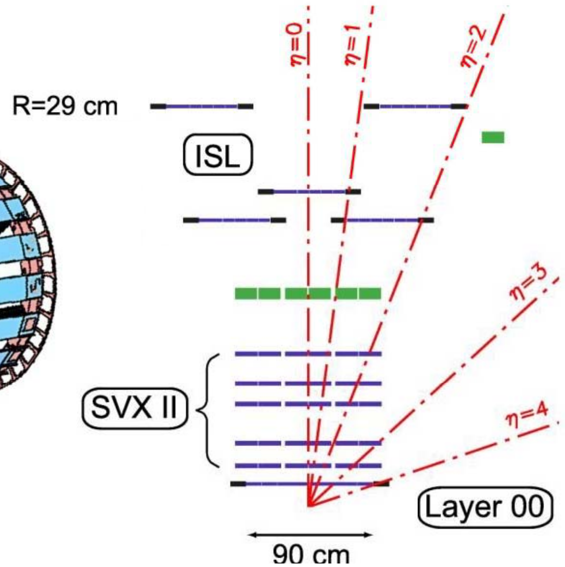
DØ Central Fiber Tracker:

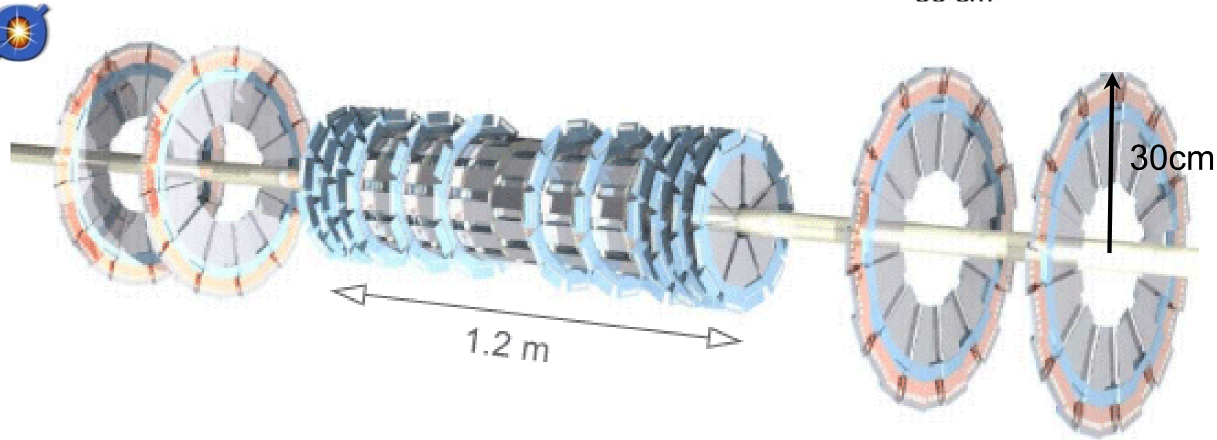
- 8 barrels of fibers: 16 hits
- 77k fibers: 200 km of scintillating fiber and 800 km of clear fiber for readout
- single hit resolution 100μm
- full coverage $|\eta| < 1.7$
- $\sigma(p_T)/p_T = 0.17\% \times p_T\,(\mathrm{GeV})$

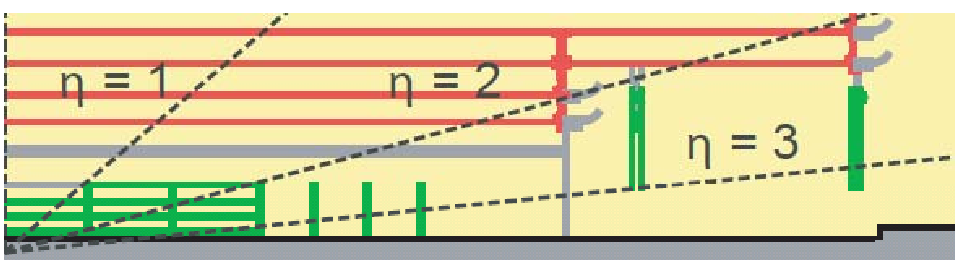
Tevatron Trackers

- Silicon Detectors









CDF:

- Barrel-only structure
- 722k channels
- Layer00 on beampipe
- full coverage $|\eta| < 2.0$
- σ_b = 35 μm @ p_T = 2 GeV

DØ:

- Barrels and disks
- 800k channels
- Layer 0 on beampipe
- full coverage $|\eta| < 2.5$
- σ_b = 15 μm for p_T >10 GeV

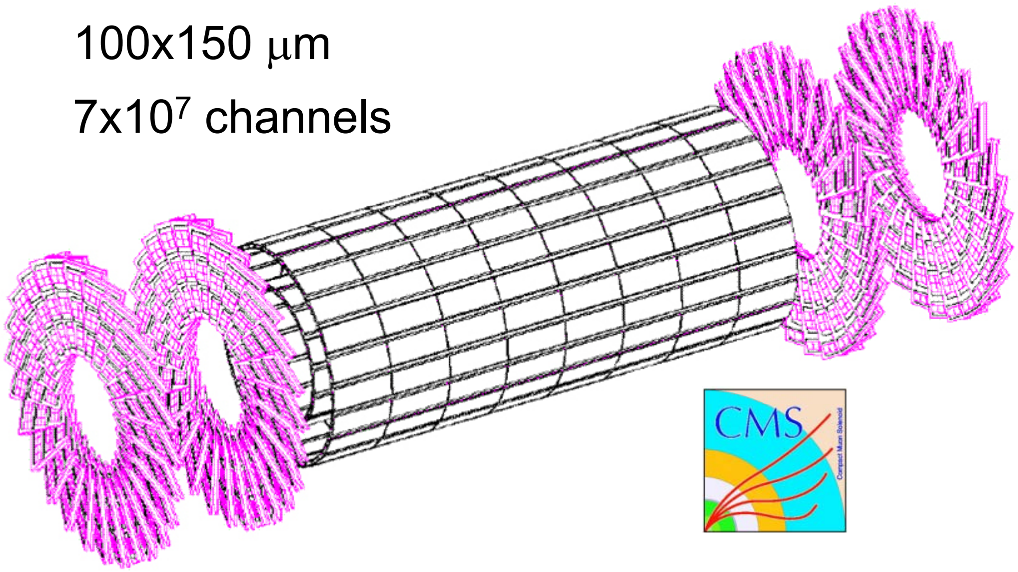
LHC Design Solutions

- Start Small: Collider Pixel Detectors

CMS Pixels:

100x150 μm

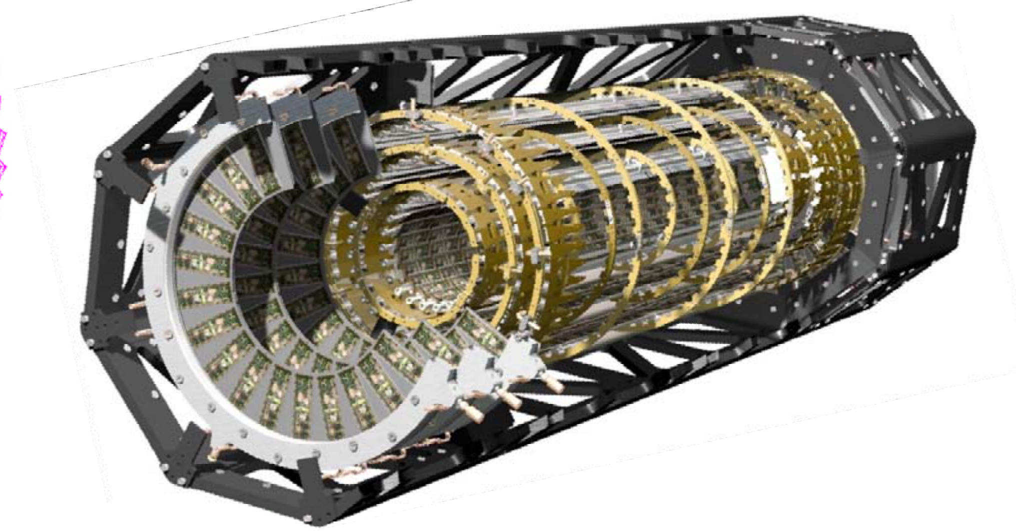
7×10^{7} channels



ATLAS Pixels:

50x400 μm

8×10^{7} channels



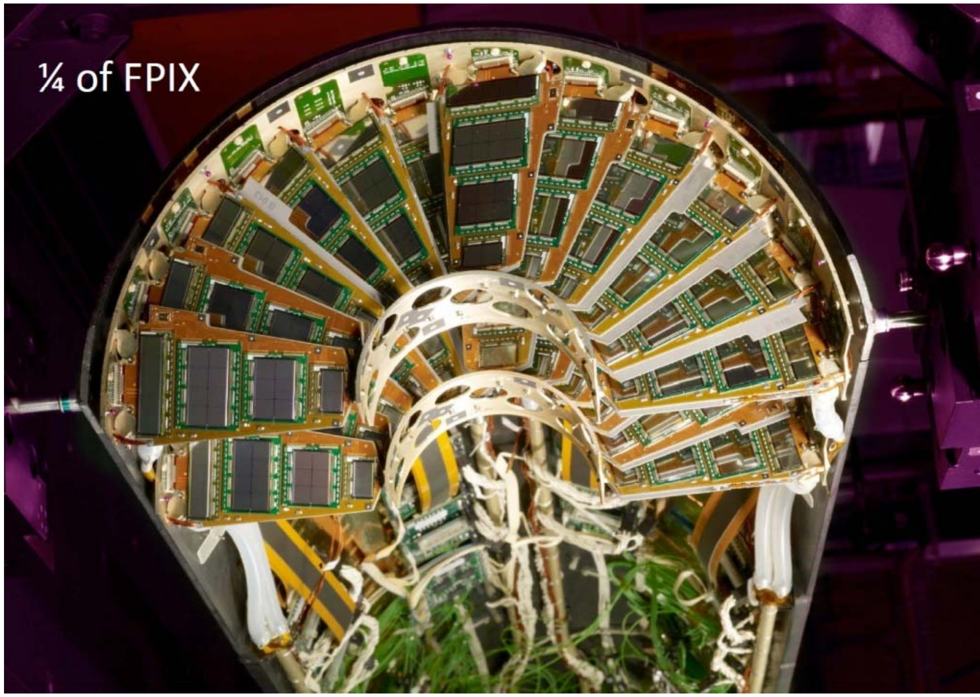
- σ (z) ~ σ (rφ) ~ 15μm
- 3 barrel layers: r =   4.3cm, 7.2cm, 11.0cm
  - $|\eta| < 1.6$
- 2 disks: $1.8 < |\eta| < 2.4$
- Tracking volume: ~1m long, 0.2m radius
- 1.06 m^2 of silicon

- σ (rφ) ~ 10μm, σ (z) ~ 115μm
- 3 barrel layers: r =   5cm, 9cm, 12cm
  - $|\eta| < 1.9$
- 3 disks: $1.9 < |\eta| < 2.5$
- Tracking volume: ~1.6m long, 0.2m radius
- 1.8 m^2 of silicon

Size?

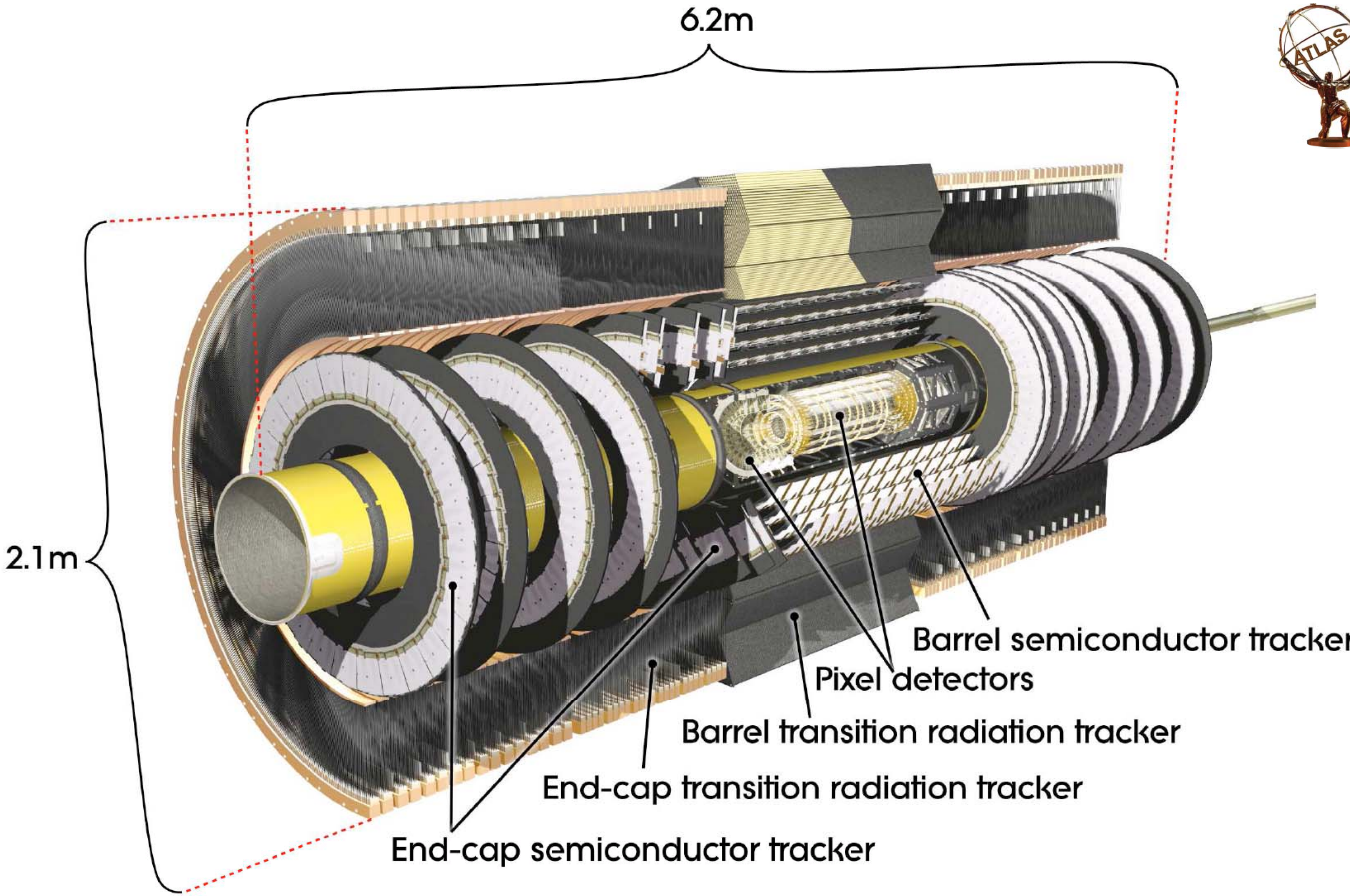
- Some parts of CMS are still small…

half of Barrel Pixels: under construction

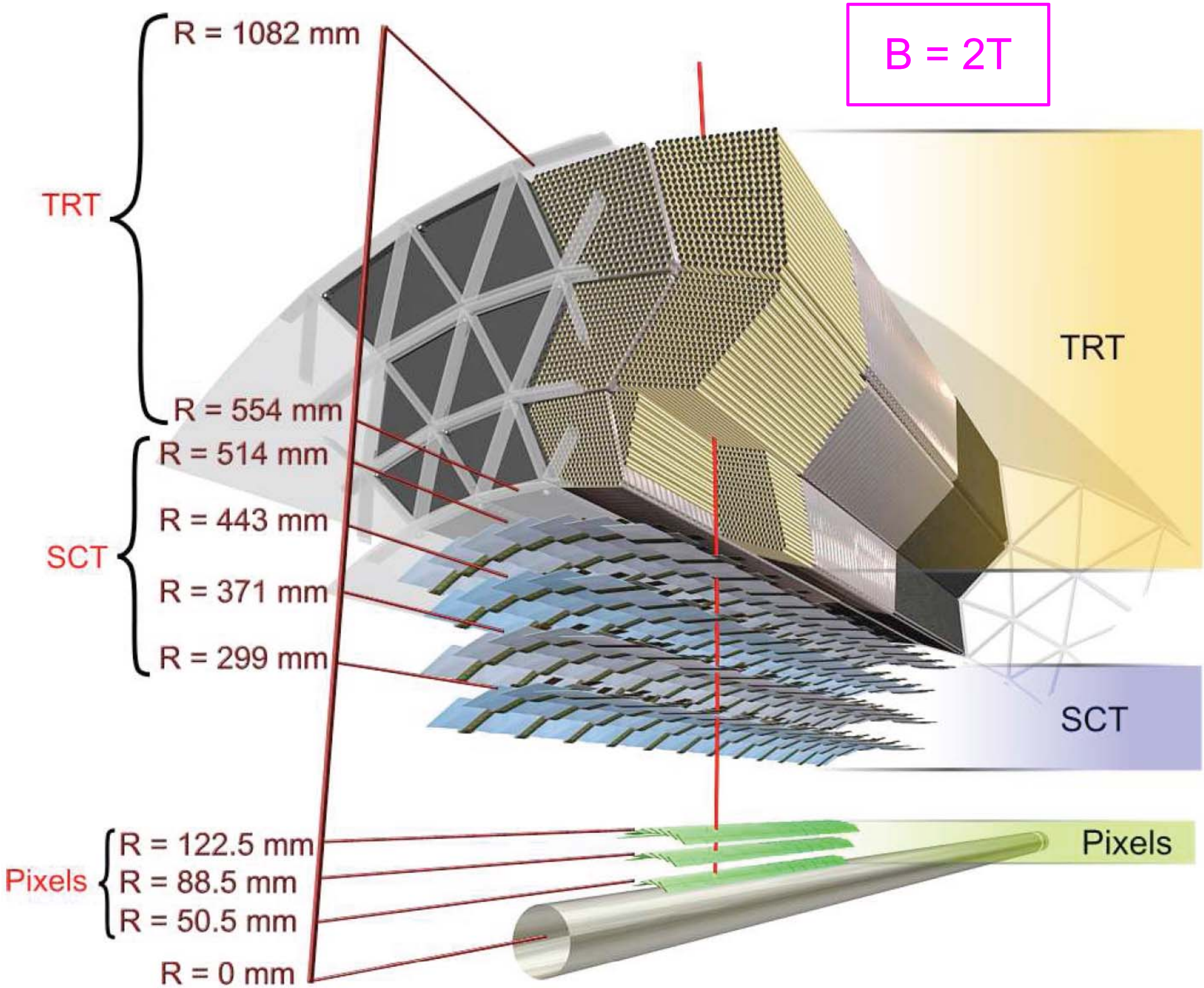


LHC pixel detectors ~ same size as Tevatron Silicon Trackers!

Main Tracking Systems: ATLAS



Main Tracking Systems: ATLAS Barrel



TRT:

- ~100k channels
- ~36 hits/track
- single hit σ_x = 130μm

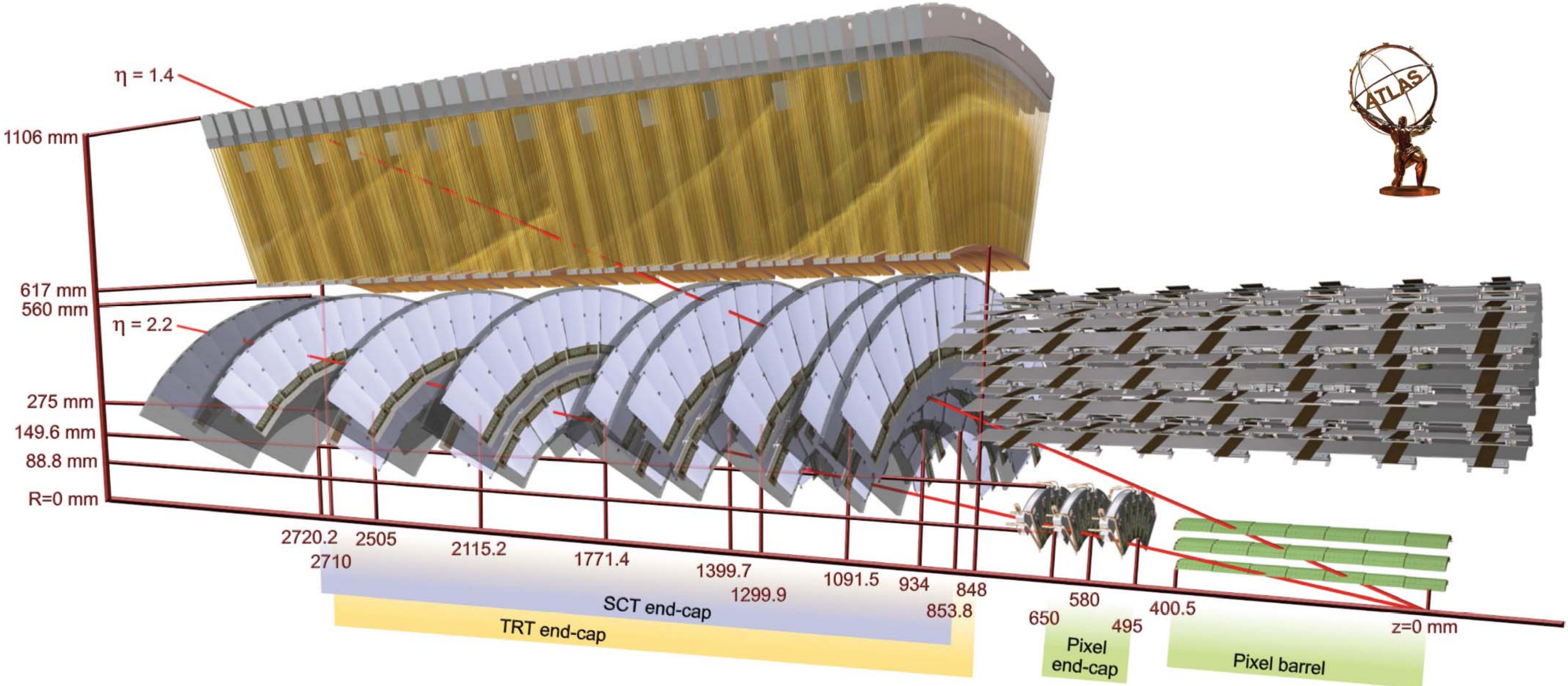
SCT:

- 6.3M channels
- 4 double barrel layers
  - 80mrad stereo angle
  - strip pitch 80 μm
  - binary readout

Performance: $(\eta = 0)$

- $\sigma(p_T)/p_T$ =
  0.038% $\times$ p_T(GeV)
- σ_b = 11 μm
  @ p_T = 1 TeV

Main Tracking Systems: ATLAS Endcap



TRT: 160 straw planes, 0.85 < $|z|$ < 2.7m

- 250k channels

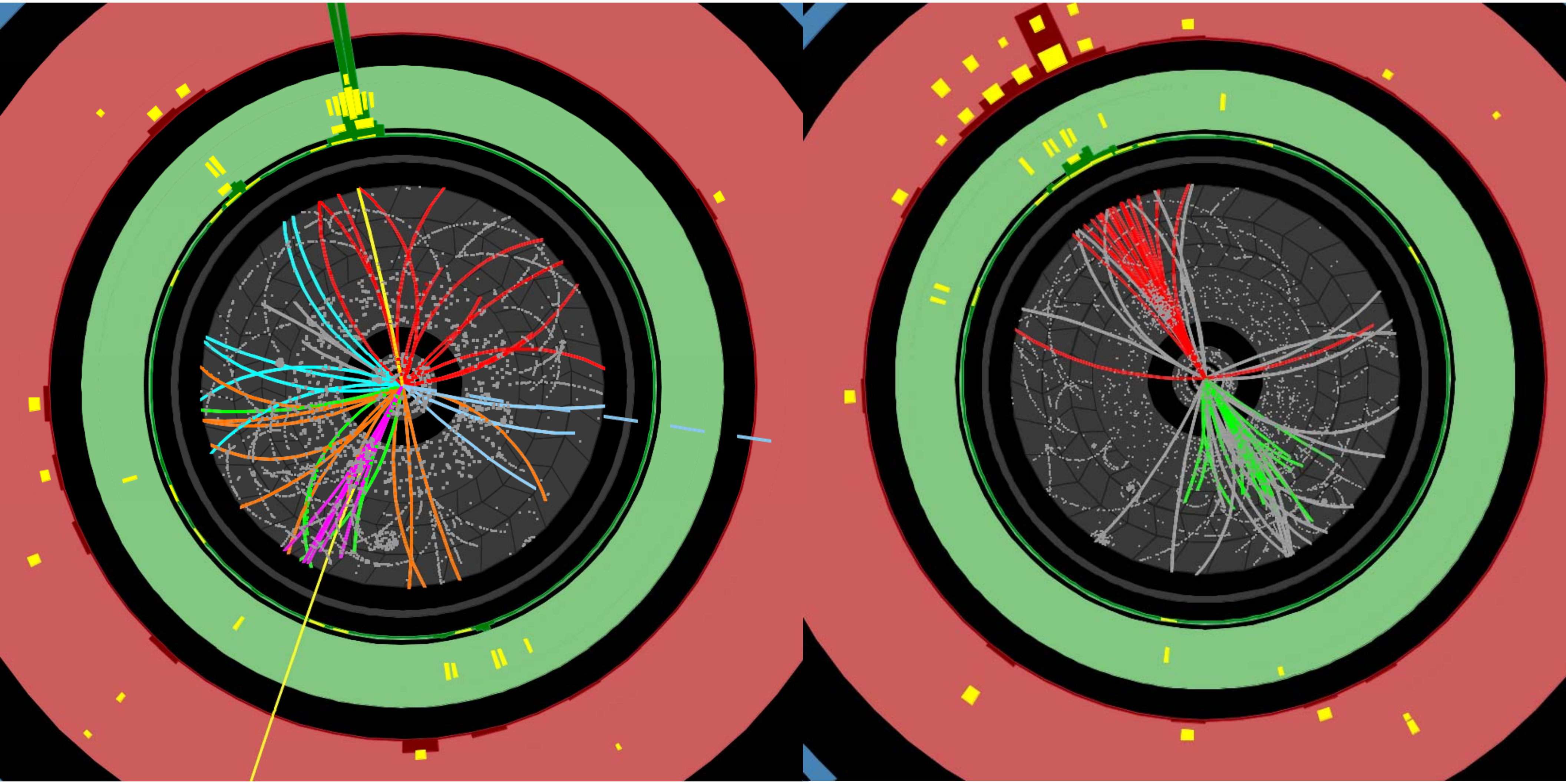
SCT: 9 double sided-disks (radial+40mrad)

- 1.5 < $|\eta|$ < 2.5

Performance: $(\eta = 2.5)$

- $\sigma(p_T)/p_T$ = 0.11% × p_T (GeV)
- σ_b = 11 μm @ p_T = 1 TeV

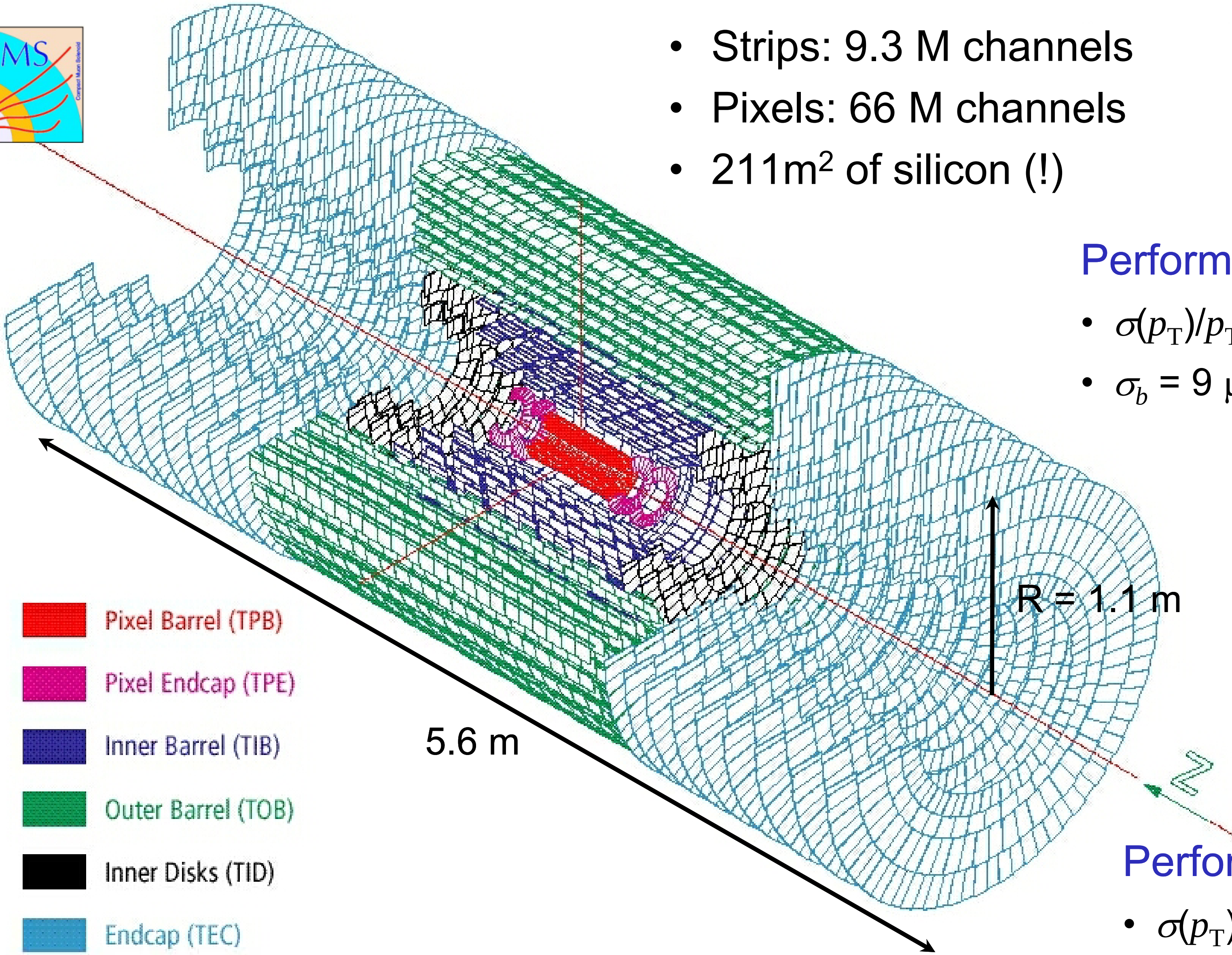
some nice event displays



Main Tracking Systems: CMS

- Strips: 9.3 M channels
- Pixels: 66 M channels
- 211m^2 of silicon (!)

B = 4T



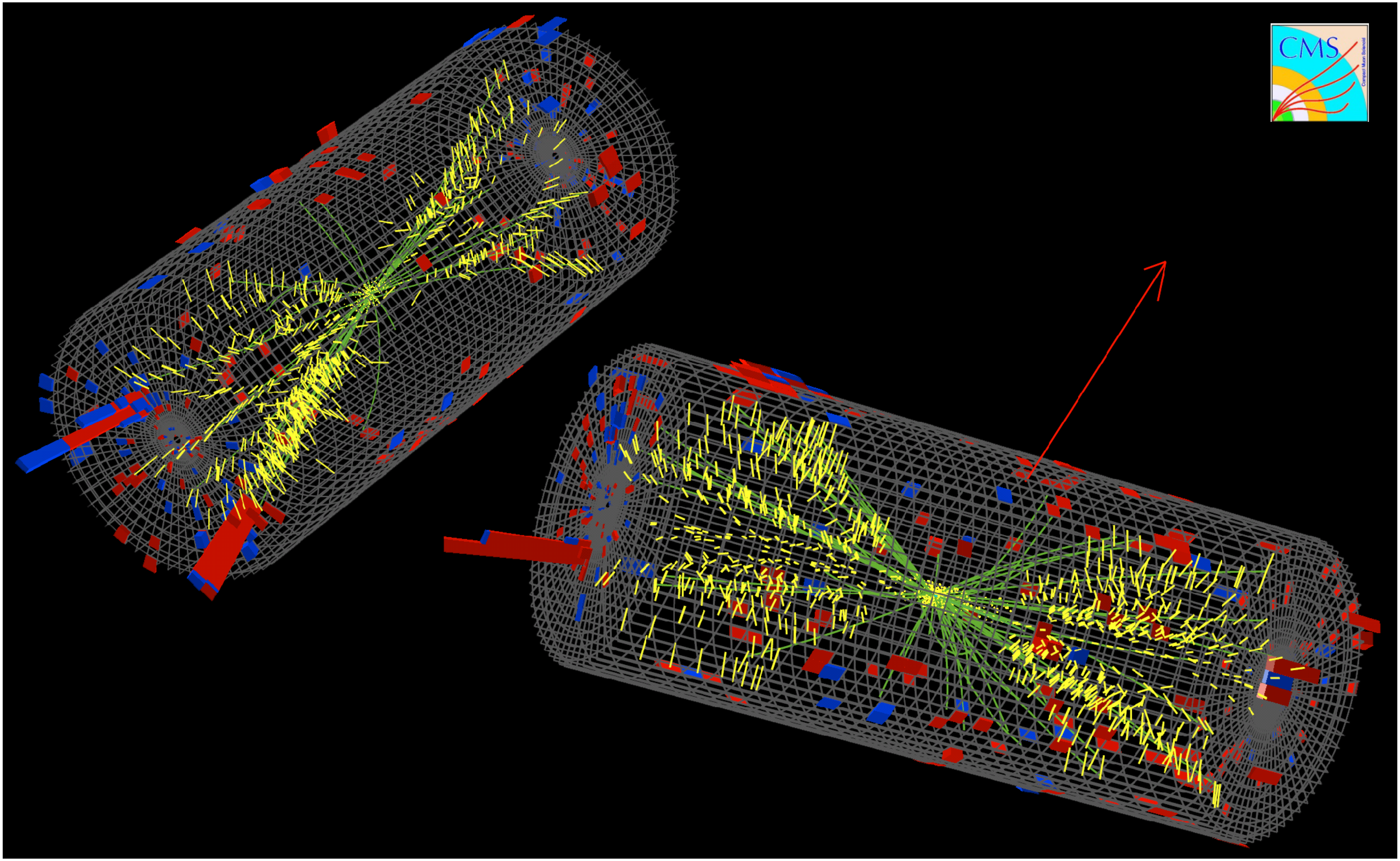
Performance: $(\eta = 0)$

- $\sigma(p_T)/p_T$ = 0.015% × p_T (GeV)
- σ_b = 9 μm @ p_T = 1 TeV

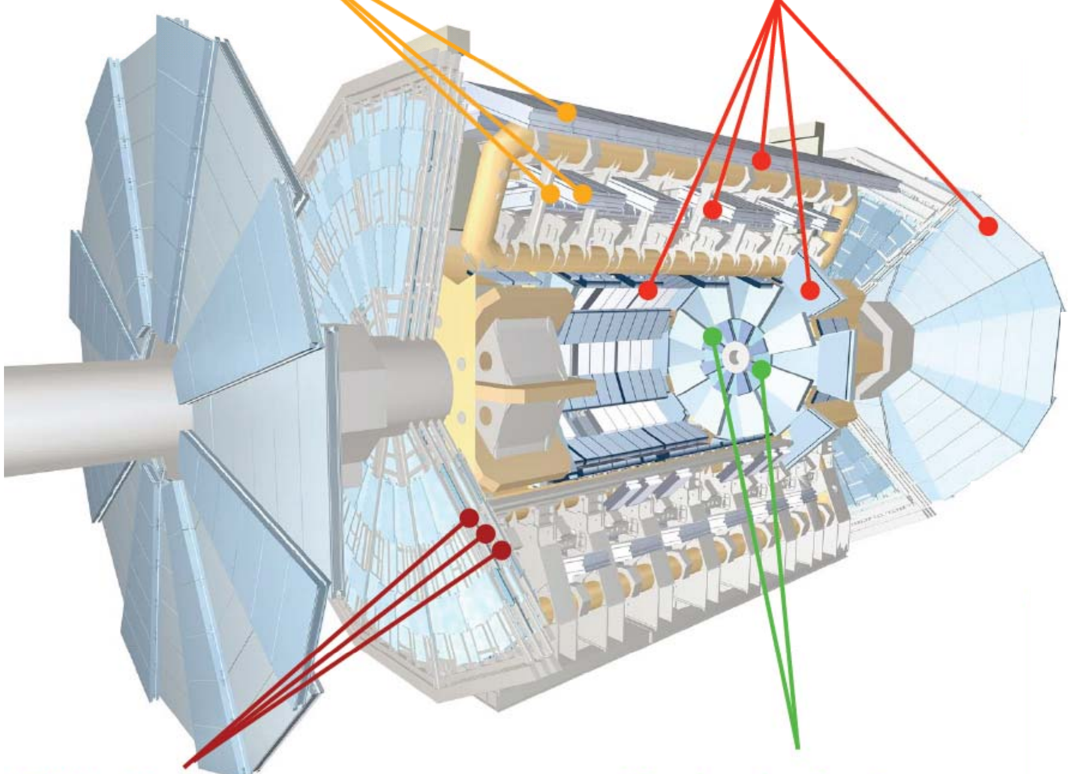
Performance: $(\eta = 2.5)$

- $\sigma(p_T)/p_T$ = 0.7% × p_T (GeV)
- σ_b = 11 μm @ p_T = 1 TeV

some nice event displays



Muon systems: also trackers!



Complicated systems:

- Must track with good precision
- nasty magnetic field variation
- must be fast enough to trigger

ATLAS:

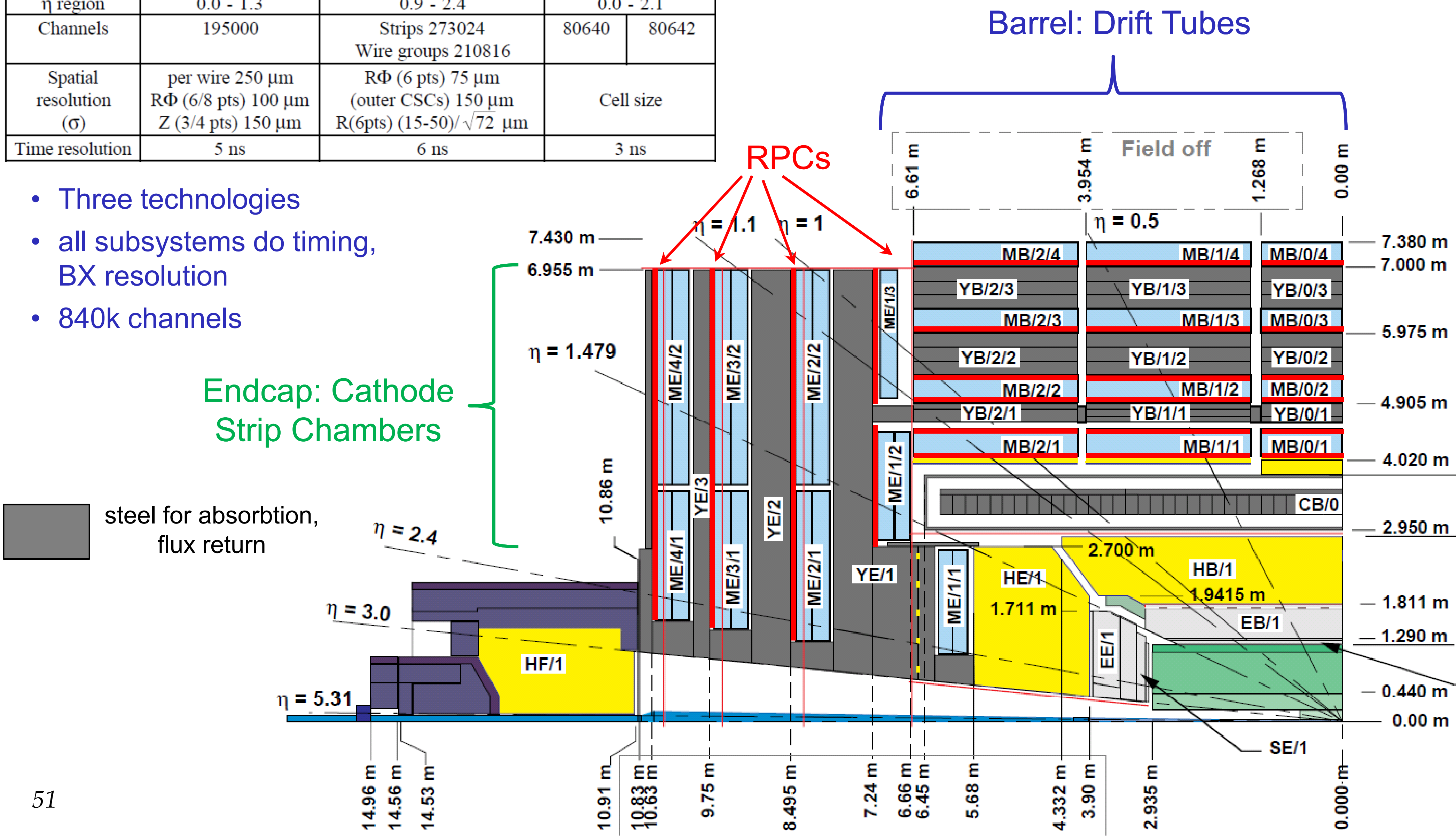
- four different technologies
- huge area: 10,000m^2
- 1 M channels
- high-precision!
- highly-evolved internal alignment system

		Chamber resolution (RMS) in			Measurements/track		Number of	
Type	**Function**	z/R	ϕ	time	barrel	end-cap	chambers	channels
MDT	tracking	35 μm (z)	—	—	20	20	1088 (1150)	339k (354k)
CSC	tracking	40 μm (R)	5 mm	7 ns	—	4	32	30.7k
RPC	trigger	10 mm (z)	10 mm	1.5 ns	6	—	544 (606)	359k (373k)
TGC	trigger	2–6 mm (R)	3–7 mm	4 ns	—	9	3588	318k

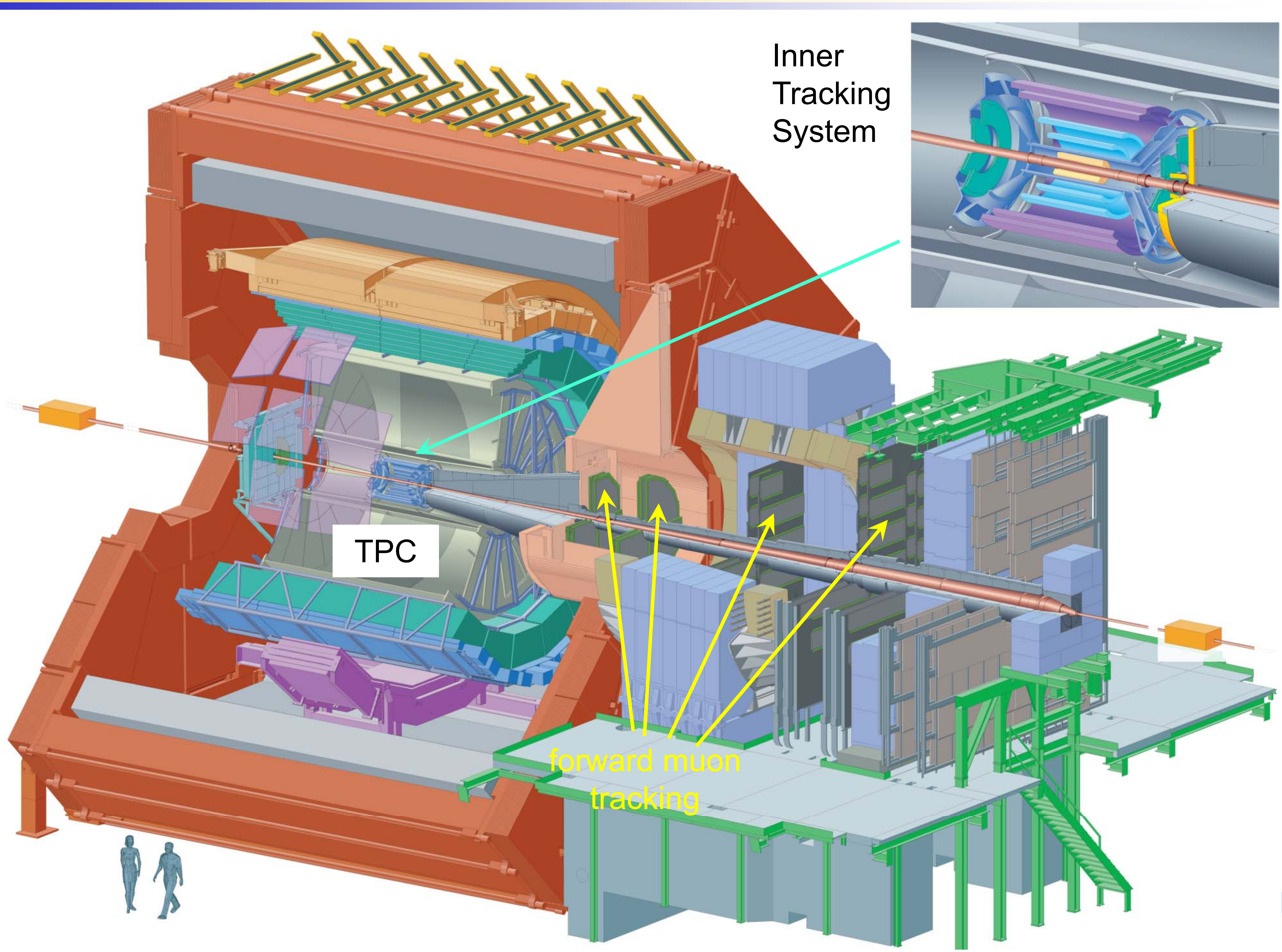
More muons

Detector	Drift Tubes	Cathode Strip Chambers	Resistive Plate	
Function	Tracking p_T trigger BXID	Tracking p_T trigger BXID	BXID p_T trigger Resolve tracking ambiguities	
η region	0.0 - 1.3	0.9 - 2.4	0.0 - 2.1	
Channels	195000	Strips 273024 Wire groups 210816	80640	80642
Spatial resolution (σ)	per wire 250 μm RΦ (6/8 pts) 100 μm Z (3/4 pts) 150 μm	RΦ (6 pts) 75 μm (outer CSCs) 150 μm R(6pts) (15-50)/$\sqrt{72}$ μm	Cell size	
Time resolution	5 ns	6 ns	3 ns	

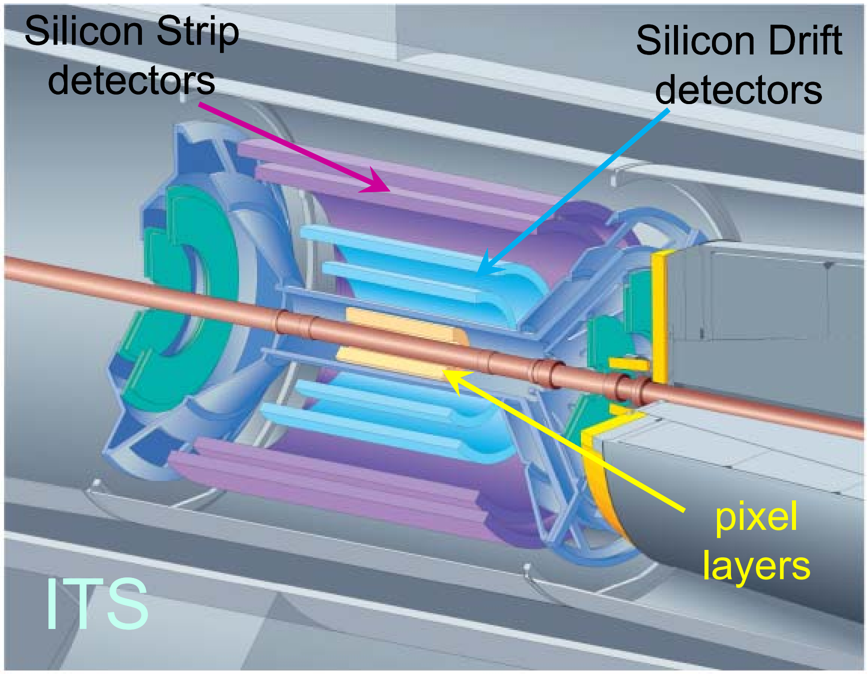
- Three technologies
- all subsystems do timing, BX resolution
- 840k channels

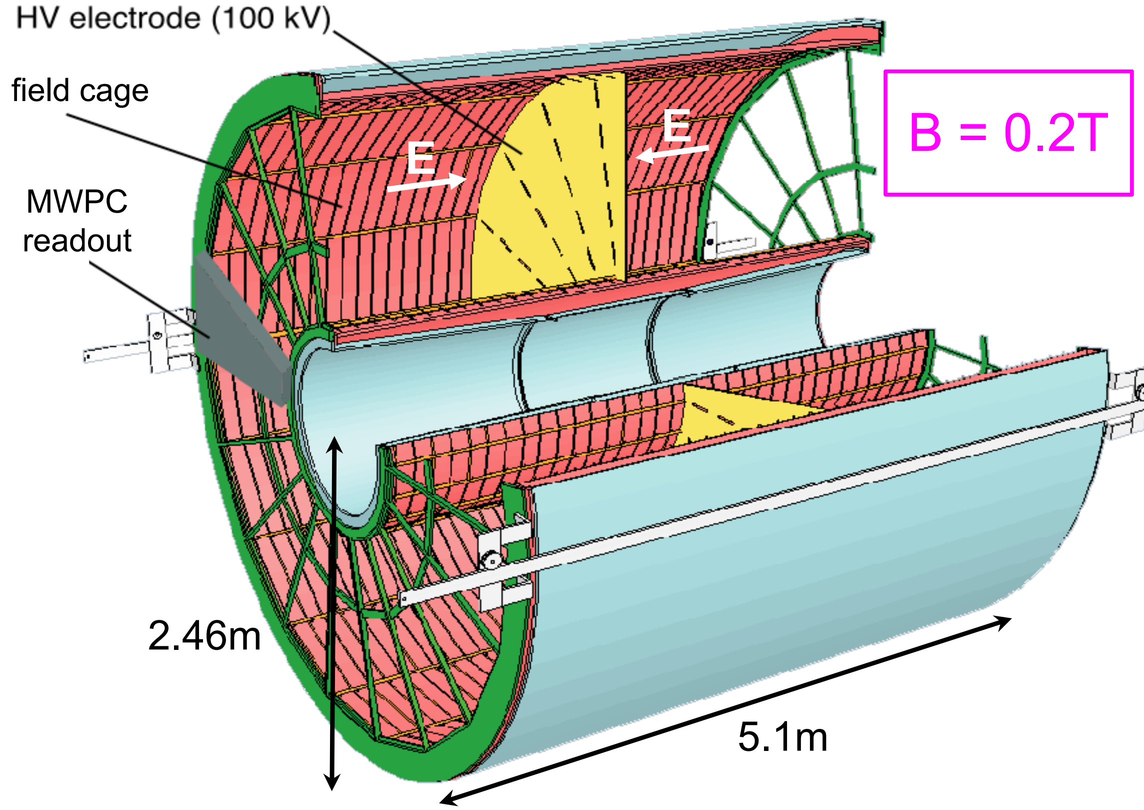


ALICE

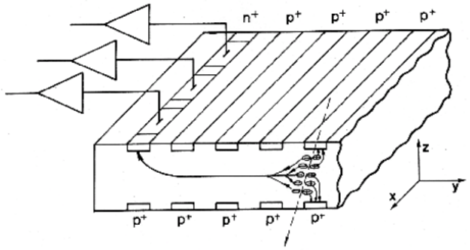


ALICE Tracking



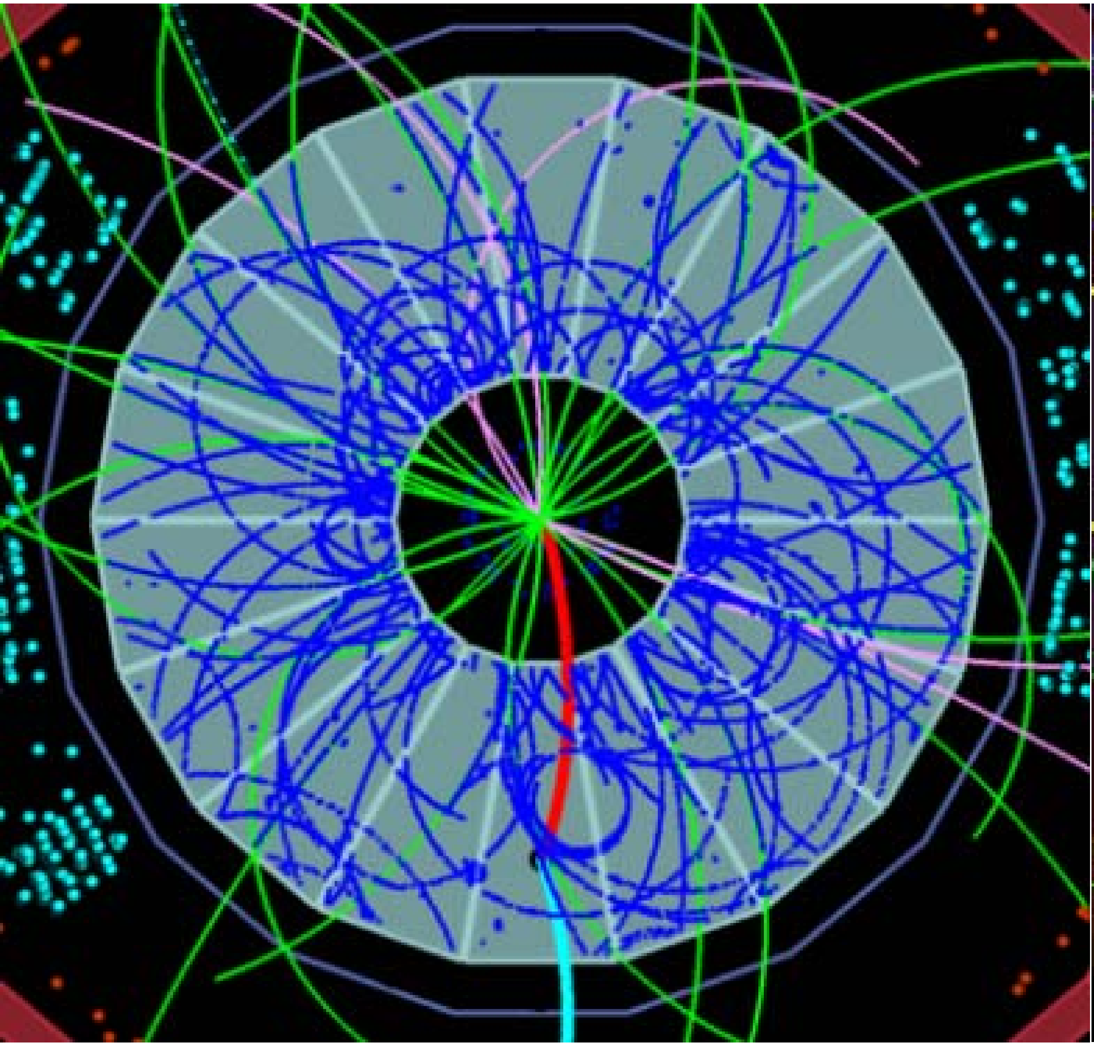
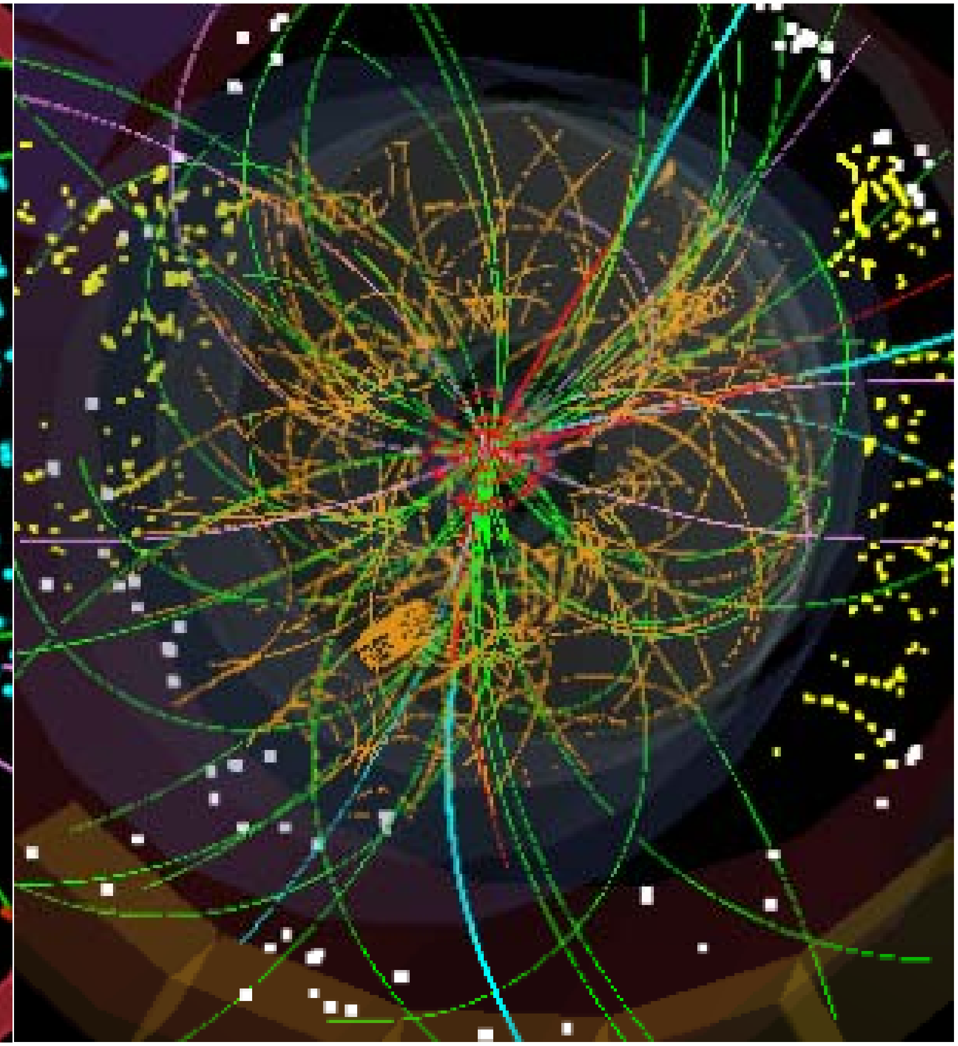


- optimized for dE/dx, stand-alone particle tracking for p_T < 100 MeV/c
- high-density, low-rate environment
- SSD: 2 layers of double-sided silicon
  - 2.7 M channels
- SDDs: 133k channels
  - *transverse* drift
- Pixels: 15.6M channels
- σ_b = 20μm, σ_z = 100μm @ p_T = 10 GeV

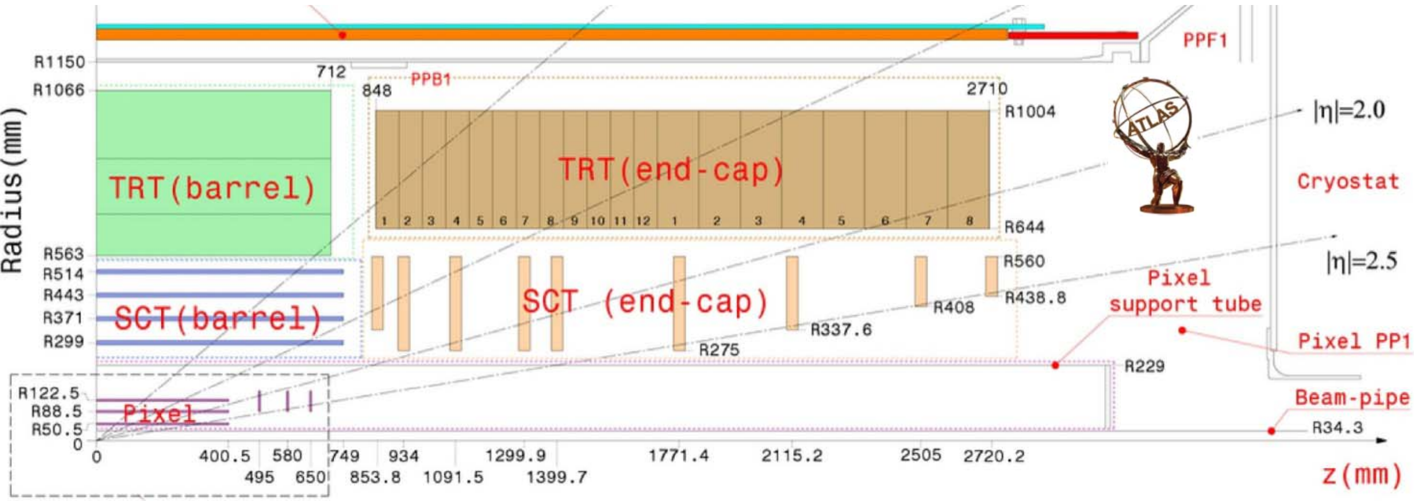


- Most ambitious TPC ever constructed
- 95m^3 gas volume; overall coverage $|\eta| < 0.9$
- 557k readout pads
- total drift time 92μs
- 1000 samples per drift time
- 8000 particles per unit of rapidity!
- $\sigma(p_T)/p_T = 0.45\% \times p_T$ (GeV)

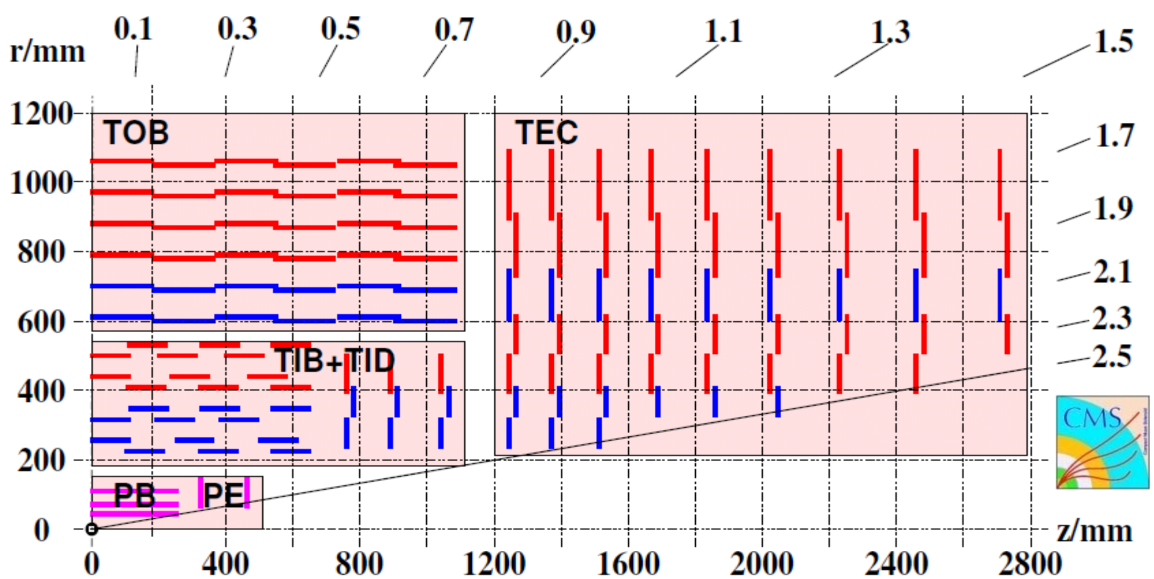
ALICE event pictures

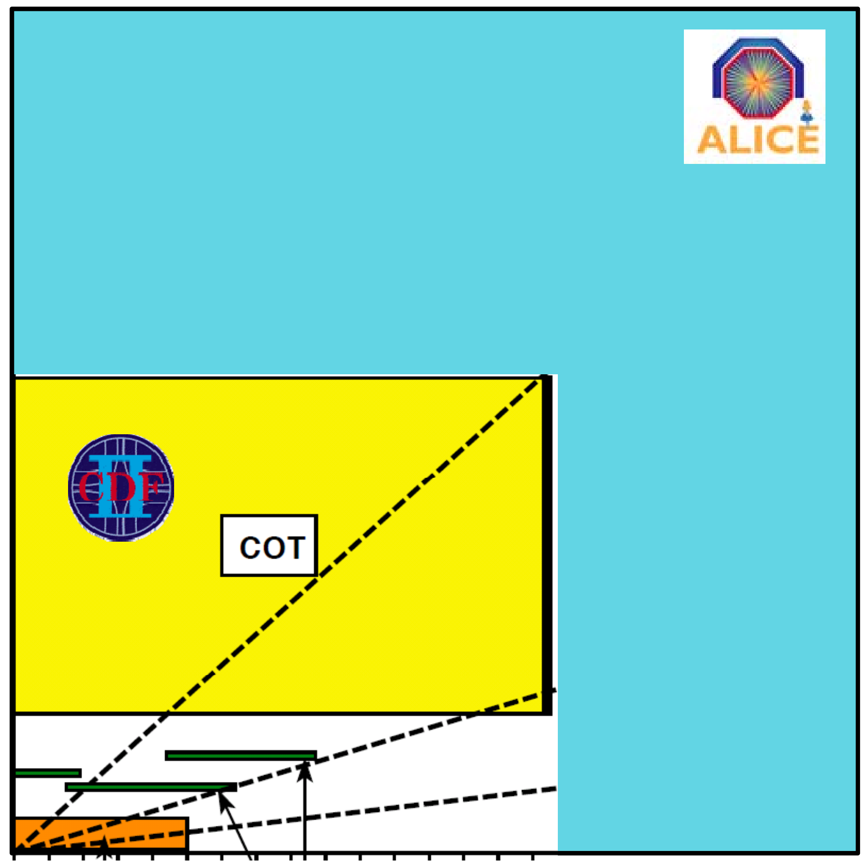



Tracker size comparison: quadrants



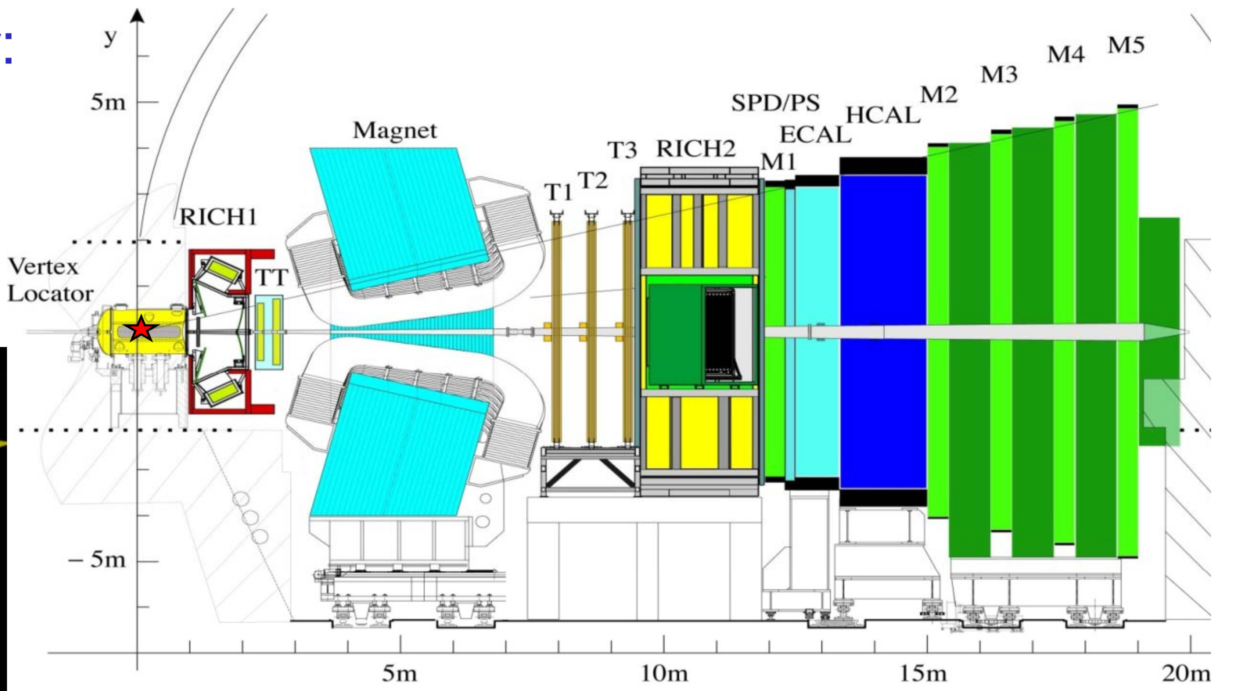
LHC 4π tracking systems make CDF look tiny!

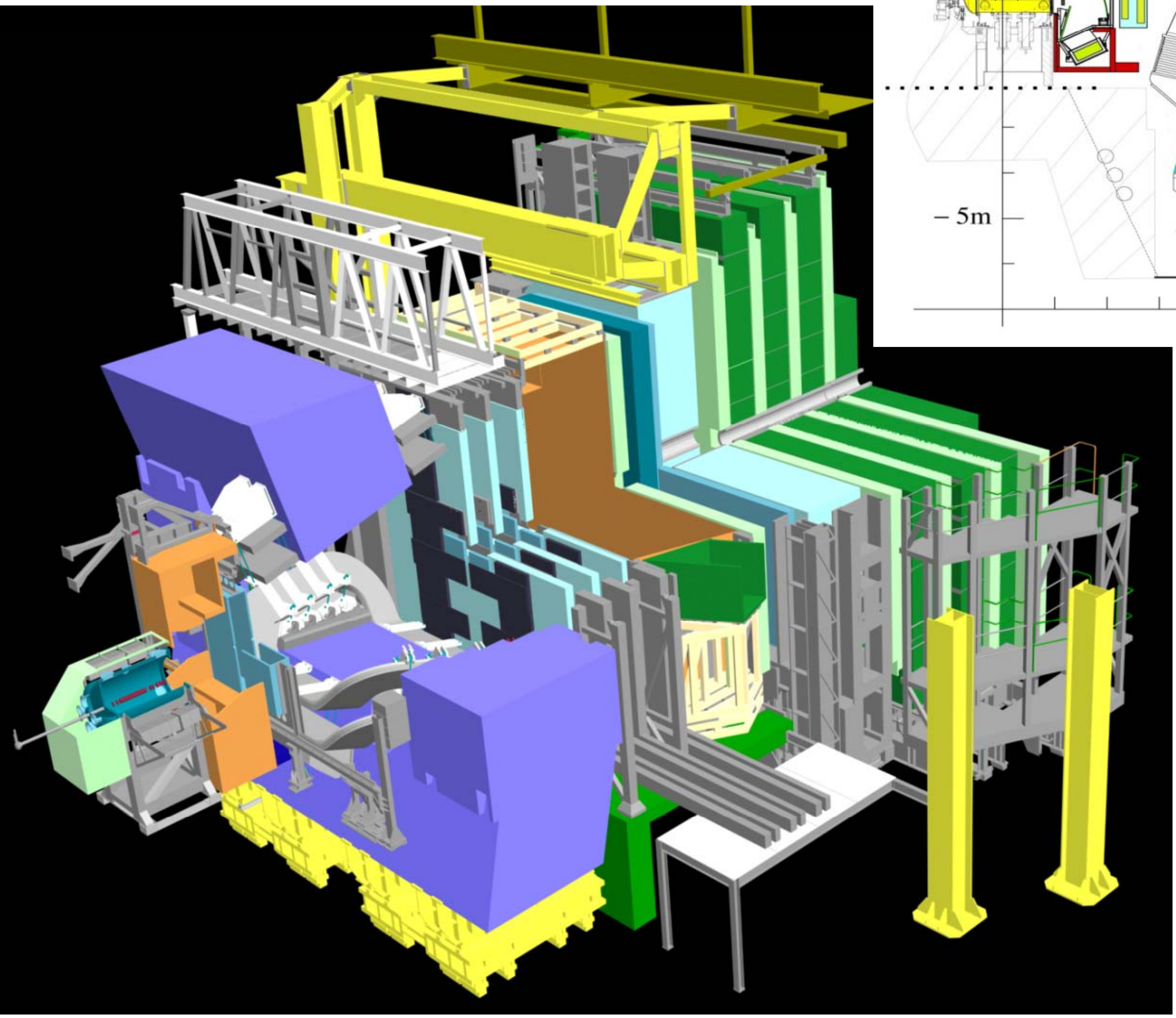




LHCb

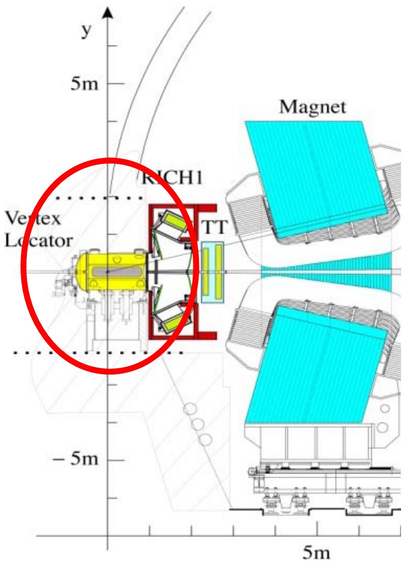
- Single-arm spectrometer:
  - *very* different geometry
  - similar requirements on precision/resolution



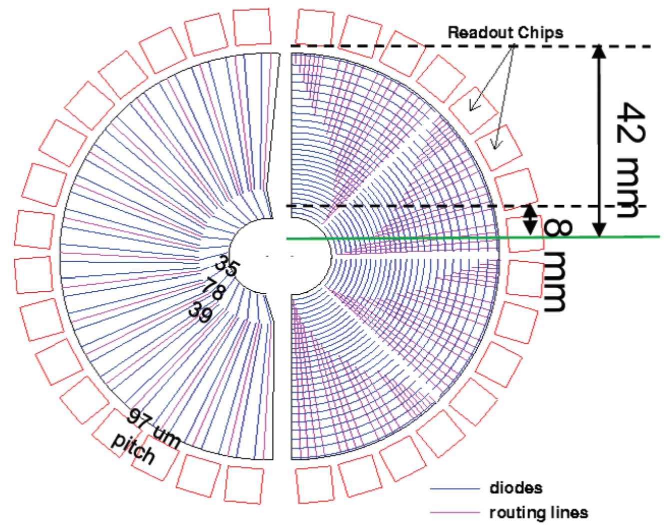


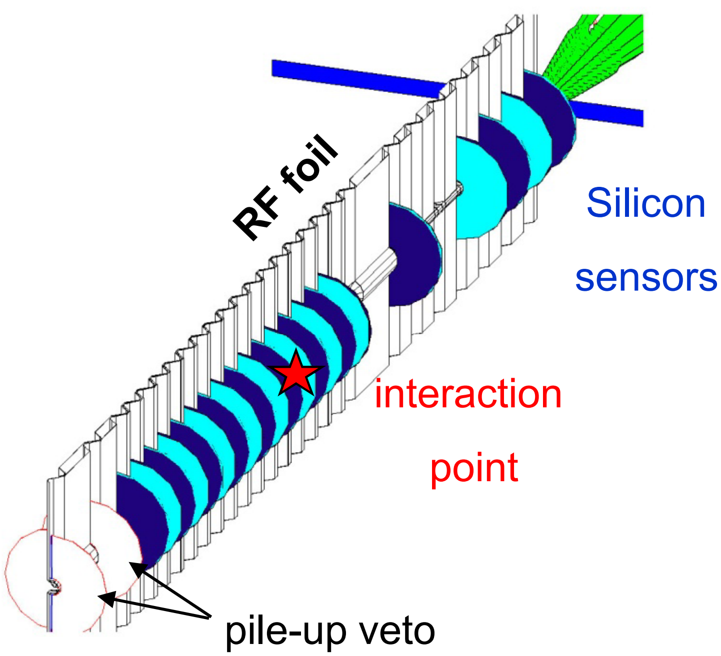
- Extremely high-rate environment
- High-precision vertexing
- Five separate tracking planes
- Dipole for momentum measurement
- Muon system: MWPC or triple GEMs
- premium placed on thin detectors

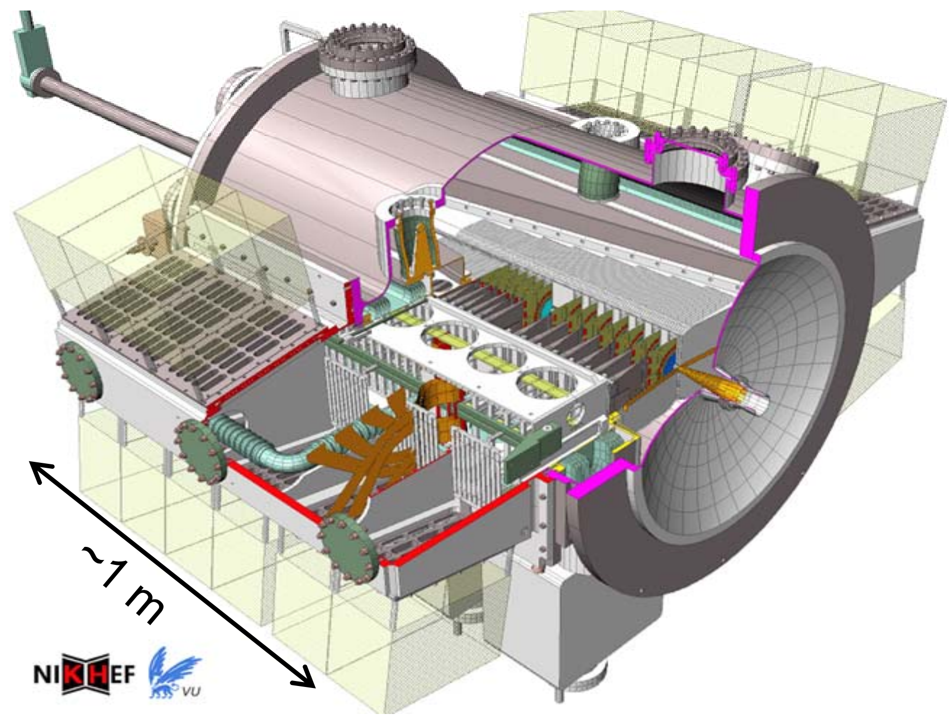
LHCb VErtex LOcator (VELO)

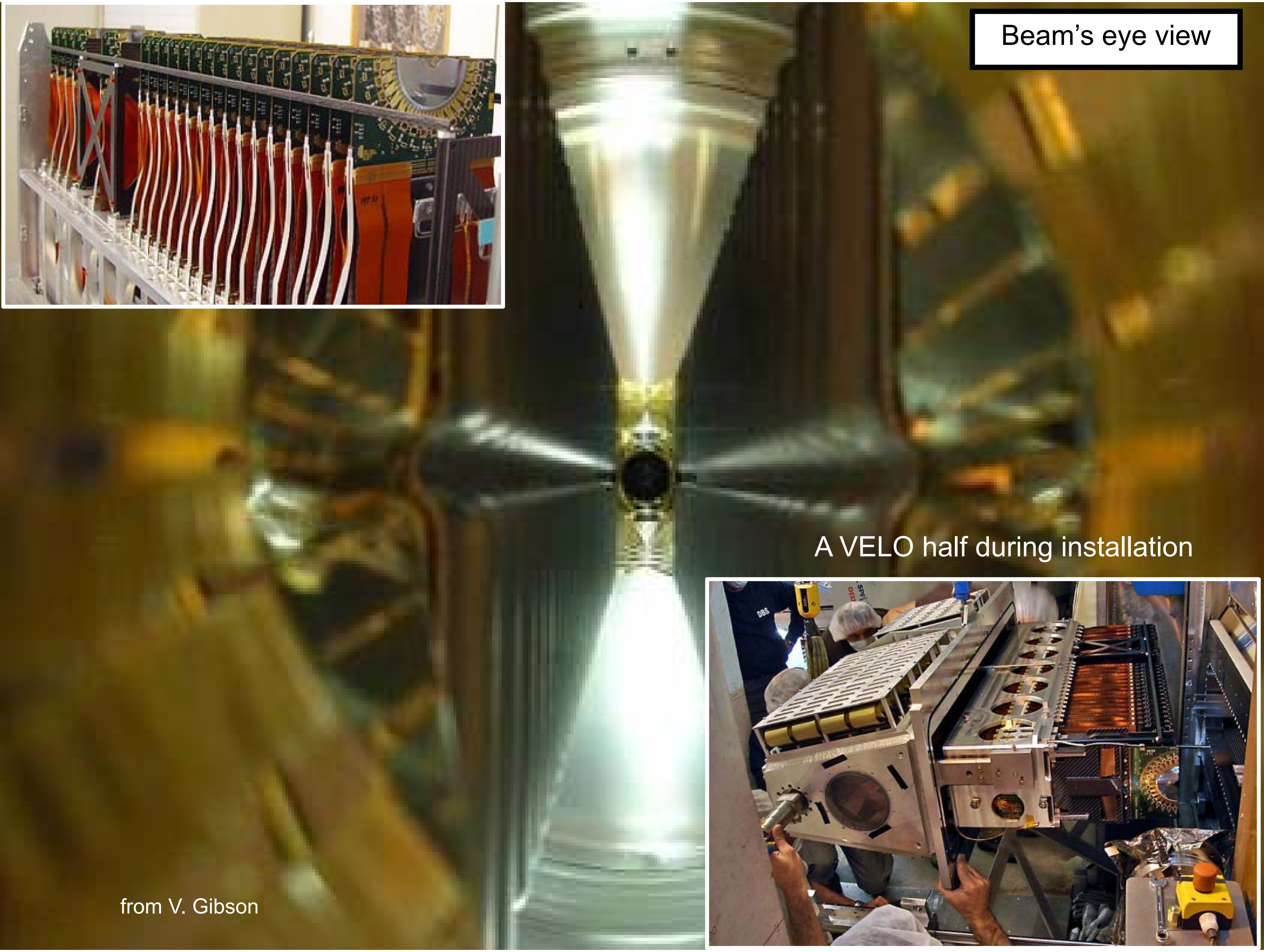


- 21 VELO stations (r and ϕ silicon sensors)
  - sensor pitch 35-100μm
  - 2x2048 channels per station
- placed in a secondary vacuum vessel
- 3cm separation, 8mm from beam!
- separated by a 300 μm of Al RF foil
- detector halves retractable for injection
- 4μm resolution, ~5μm variation fill-to-fill

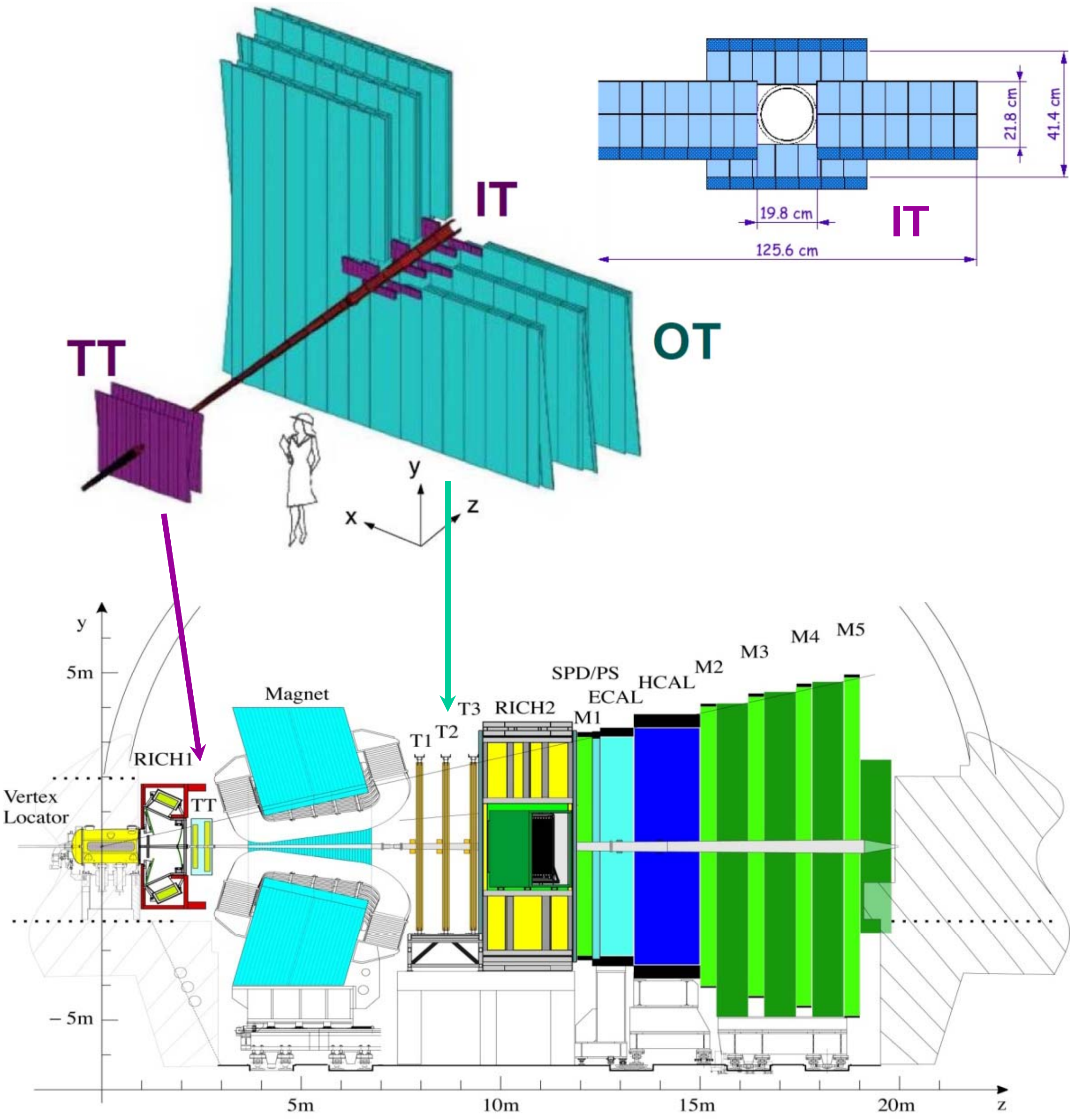







Beam's eye view
A VELO half during installation
from V. Gibson

LHCb: other tracking



TT:

- four planes of Silicon Strips
  - 0°, +5°, -5°, 0° (XUVX)
  - 183μm readout pitch
  - 55μm resolution/hit
  - 8.2 m^2; 140k channels

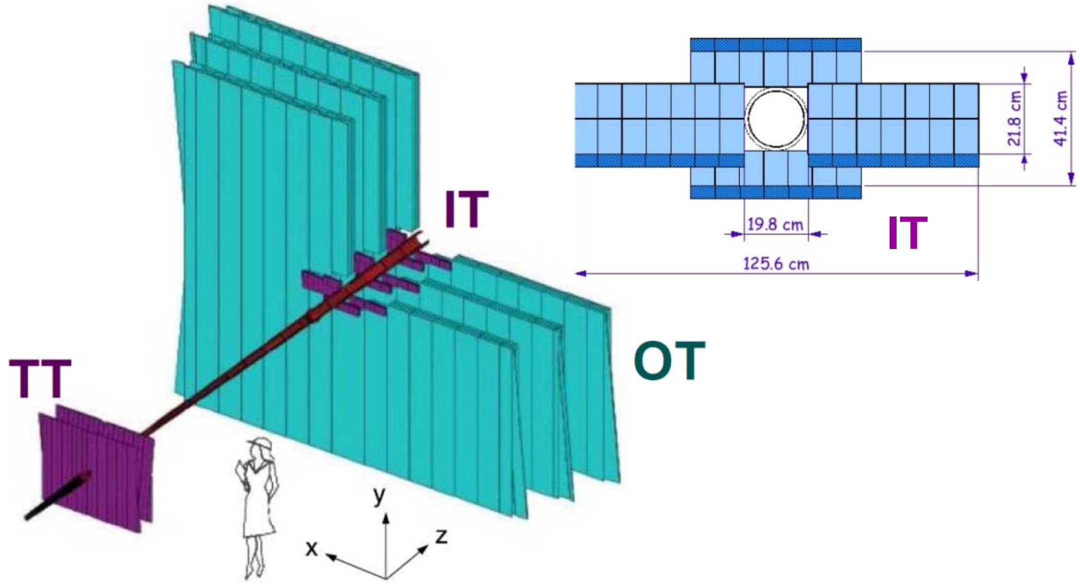
IT:

- three stations of Silicon Strips
  - 4 XUVX layers each
  - 198 μm readout pitch
  - 55μm resolution/hit
  - 4 m^2; 130k channels

OT:

- three layers of straw tubes
  - each 0°, +5°, -5°, 0° (XUVX)
  - 5mm straws
  - 250μm resolution/hit
  - 56k channels

LHCb: other tracking



S. Borghi (ICHEP)

Performance:

- Primary vertex resolution (x,y,z):
  - achieved (16, 15, 91) μm
  - expect (11, 11, 57) μm
- Impact parameter resolution (both planes):
  - achieved 16μm, expect 11μm ultimately
- $\sigma(p_T)/p_T \sim 0.45\% \times p_T$ (GeV)

TT:

- four planes of Silicon Strips
  - 0°, +5°, -5°, 0° (XUVX)
  - 183μm readout pitch
  - 55μm resolution/hit
  - 8.2 m^2; 140k channels

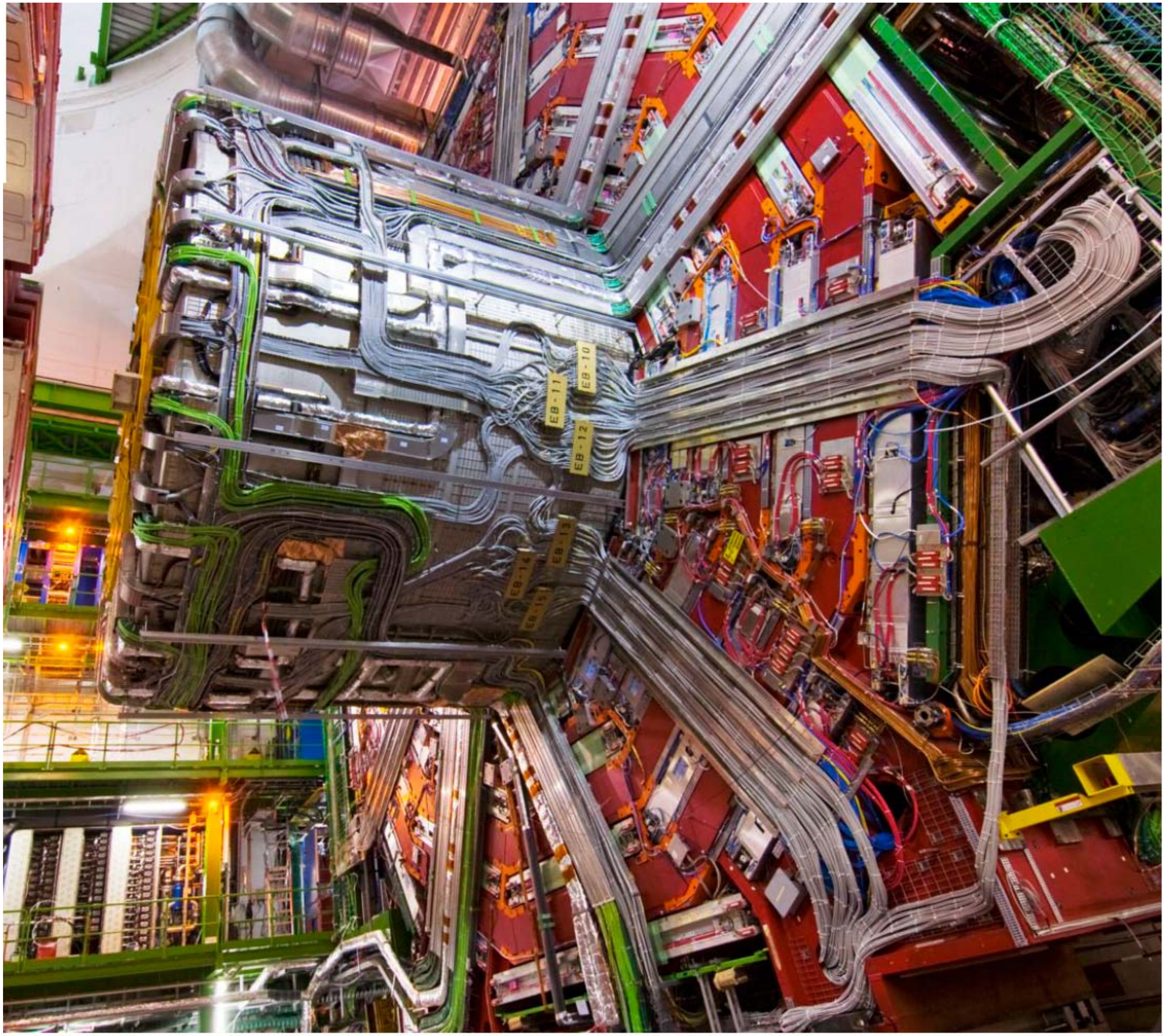
IT:

- three stations of Silicon Strips
  - 4 XUVX layers each
  - 198 μm readout pitch
  - 55μm resolution/hit
  - 4 m^2; 130k channels

OT:

- three layers of straw tubes
  - each 0°, +5°, -5°, 0° (XUVX)
  - 5mm straws
  - 250μm resolution/hit
  - 56k channels

Engineering considerations



Services:

- Example: CMS

Microstrip tracker	Pixels
~210 m^2 of silicon, 9.3M channels	~1 m^2 of silicon, 66M channels
73k APV25s, 38k optical links, 440 FEDs	16k ROCs, 2k olinks, 40 FEDs
27 module types	8 module types
~34kW	~3.6kW (post-rad)

- – Translations: APV = ROC = readout chip, FED = front end electronics
- – 40k individual optical links for readout: thousands of cables
- – Mechanically complicated: 35 different structures x thousands of pieces
- – Cooling! ~ 40kW to conduct out of a volume cooled to -10C
- – Don't forget about support structure engineering:
  - must be stiff, thin, with zero thermal expansion coefficient
- – built-in alignment infrastructure: Laser systems, other optics

Cost per channel (CHF)

Item	ALICE	ATLAS	CMS	LHCb
pixel sensors	0.02	0.05	0.02	3.23
pixel Total	0.17	0.18	0.13	24.56
Si Strips	1.88	3.46	0.99	9.82
Si Total	5.82	7.23	6.68	24.71
Outer Sensors	7.68	25.39		49.47
Outer Total	30.60	48.40		169.14
Total Cost (kCHF)	**35976**	**77211**	**70685**	**21055**

- Note: My numbers, taken from TDRs and inflation-adjusted to 2004 CHF
- for LHCb, pixel = VELO
- looks like CMS got a volume discount
    - ATLAS cost breakdown for sensors probably includes some other items
- silicon sensors are very cheap compared to infrastructure, readout electronics

Conclusions

- All “modern” experiments require state-of-the-art tracking systems
  – highest possible resolution commensurate with cost, engineering
  – performance parameters not that different overall

Backup Slides

p-n junctions and Reverse Bias

image from
Wikipedia